July 2002
NSF 02/01/EPAWW399

Environmental Technology Verification Report

Performance of Induction Mixers for Disinfection of Wet Weather Flows

USFilter/Stranco Products Water Champ® F Series Chemical Induction System

Prepared by

NSF International

Under a Cooperative Agreement with
EPA U.S. Environmental Protection Agency

ETV ETV ETV

THE ENVIRONMENTAL TECHNOLOGY VERIFICATION PROGRAM

U.S. Environmental Protection Agency

NSF International

ETV Joint Verification Statement

TECHNOLOGY TYPE:	**Induction Mixer**
APPLICATION:	**Disinfection of Wet-Weather Flows**
TECHNOLOGY NAME:	**Water Champ® F Series Chemical Induction System**
COMPANY:	**USFilter/Stranco Products**
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The U.S. Environmental Protection Agency (EPA) has created the Environmental Technology Verification (ETV) Program to facilitate the deployment of innovative or improved environmental technologies through performance verification and dissemination of information. The goal of the ETV program is to further environmental protection by substantially accelerating the acceptance and use of improved and more cost-effective technologies. ETV seeks to achieve this goal by providing high quality, peer reviewed data on technology performance to those involved in the design, distribution, permitting, purchase, and use of environmental technologies.

ETV works in partnership with recognized standards and testing organizations; stakeholders groups which consist of buyers, vendor organizations, and permitters; and with the full participation of individual technology developers. The program evaluates the performance of innovative technologies by developing test plans that are responsive to the needs of stakeholders, conducting field or laboratory tests (as appropriate), collecting and analyzing data, and preparing peer reviewed reports. All evaluations are conducted in accordance with rigorous quality assurance protocols to ensure that data of known and adequate quality are generated and that the results are defensible.

NSF International (NSF) in cooperation with the EPA operates the Wet-Weather Flow (WWF) Technologies Program, a part of the Water Quality Protection Center, one of six Centers under ETV. The WWF Program recently evaluated the performance of a chemical induction system that can be used in the disinfection of wet weather flows such as combined sewer overflows and sanitary sewer overflows. This verification statement provides a summary of the test results for the Water Champ® F Series Chemical Induction System manufactured by USFilter/Stranco

Products. Alden Research Laboratory, Inc, performed the verification testing as the designated ETV Field Testing Organization, using the facilities of USGS's Conte Anadromous Fish Research Center, Turners Falls, Massachusetts.

TECHNOLOGY DESCRIPTION

Induction mixers are mechanical mixers that can inject and disperse both gaseous and liquid chemicals into potable water, process water or wastewater. Induction mixers can draw chemicals from the point of chemical storage to the point of injection, and disperse the chemical into the water. The dual functionality of the induction mixer essentially eliminates the need for a separate injection system and diffuser system as commonly found in typical mixing installations.

The major components of an induction mixer are:

- A submersible motor with a propeller shaft,
- A uniquely shaped propeller, and
- A vacuum body surrounding the propeller shaft.

The submersible motor spins the propeller shaft and uniquely shaped propeller in excess of 3000 rpm. The rotation of the propeller causes a reduction in pressure in the vacuum body surrounding the propeller shaft. This reduced pressure is used to draw chemical from the storage location into the induction port. The chemical is then propelled outward by the rotating propeller and mixed vigorously with the water.

Induction mixers have many applications, most of which include the transferring of a chemical (either gaseous or liquid) into a potable water, process water or wastewater. Induction mixers are most commonly used for chemical disinfection of potable water or secondary treated wastewater. Induction mixers are effective disinfection mixers because they provide a rapid and thorough dispersion of disinfectant that greatly improves the reaction between the chemical disinfectant and the water. This translates into chemical disinfectant and energy savings.

Recently, induction mixers have been used for the disinfection of wet-weather flows. However, because wet-weather flows are typically characterized by fluctuating flow rates, the performance of these mixers may vary as compared to their use for potable water or wastewater disinfection applications where flows are relatively constant. The performance of an induction mixer can be assessed by the following three parameters:

1. The size of the plume in which the chemical is transferred,
2. The uniformity of the chemical concentration within the plume, and
3. The rate at which the chemical reaches the extents of the plume.

These performance criteria are reported in this verification study in the following manner:

1. Isopleth diagrams showing the size of the plume into which the chemical can be transferred,
2. The uniformity of the chemical concentration within the plume as defined by the mix factor, and

3. The rate at which the chemical reaches the extents of the plume as identified graphically by the isopleth diagrams.

For this induction mixer verification study, different size induction mixers were operated and these parameters measured at a hydraulic laboratory where clean water was used as a surrogate to wet-weather flow and a tracer dye was used as a surrogate to the chemical disinfectant. Using this controlled laboratory approach provided greater accuracy in measuring the size and uniformity of the chemical plume created by the induction mixer. The objective of the study was to verify the achievement of effective mixing within the designated parameters of the testing program.

VERIFICATION TESTING DESCRIPTION

Test Facility

Testing was performed at the S.O. Conte Anadromous Fish Research Center (CAFRC), Turners Falls, Massachusetts. The CAFRC is a hydraulic laboratory, consisting of three indoor flumes (10 ft wide, 10 ft deep, and 104 ft in length) with a total capacity of 150 ft^3/s. For this verification study one of the three flumes was modified in size so that the induction mixers could be tested at specified channel dimensions and flow velocities. Water was directed to the test flume in the building via an inlet structure on the bank of the large canal on which the CAFRC is located.

Each induction mixer was tested in a rectangular flume, incorporating a channel section 7 ft wide with a water depth of 7 ft. To provide for a relatively uniform velocity distribution at the mixer, the length of the flume upstream of the mixer was 20 ft, and the test channel entrance was rounded to avoid flow separation. Upstream of the test channel entrance, the flow was guided by a straight flume 10 ft wide and 32 ft long, with an upstream flow distributor. Downstream of the mixer, the test flume was 28 ft long before expanding to the wider 10 ft flume width. Provisions were made to accommodate installation of the mixer at the designated location in the test flume, in accordance with instructions and mounting hardware from the manufacturer.

Methods and Procedures

USFilter/Stranco Products provided a 5 HP, 10 HP and 20 HP induction mixer for verification testing. Each induction mixers was installed in the test flume, and tested separately under nominal flow velocities of 0.5 ft/s, 1.25 ft/s, and 3.0 ft/s. For each test, the flow velocity was held steady at a water depth of 7 ft and the mixer was operated with a tracer dye as a surrogate for the chemical disinfectant. A sampling rig was positioned at locations 5 ft, 10 ft, and 15 ft downstream of the mixer to collect samples over the entire cross section of the flume. The size and nature of the "chemical" plume was characterized by measuring the dye concentration over the entire cross section of the flume. Figure VS-1 describes the test conditions under which samples were collected during the verification testing.

5 HP mixer operated at **0.5** ft/s and samples taken at **5, 10 and 15** ft downstream of mixer.	**5** HP mixer operated at **1.25** ft/s and samples taken at **5, 10 and 15** ft downstream of mixer.	**5** HP mixer operated at **3.0** ft/s and samples taken at **5, 10 and 15** ft downstream of mixer.
10 HP mixer operated at **0.5** ft/s and samples taken at **5, 10 and 15** ft downstream of mixer.	**10** HP mixer operated at **1.25** ft/s and samples taken at **5, 10 and 15** ft downstream of mixer.	**10** HP mixer operated at **3.0** ft/s and samples taken **at 5, 10 and 15** ft downstream of mixer.
20 HP mixer operated at **0.5** ft/s and samples taken at **5, 10 and 15** ft downstream of mixer.	**20** HP mixer operated at **1.25** ft/s and samples taken at **5, 10 and 15** ft downstream of mixer.	**20** HP mixer operated at **3.0** ft/s and samples taken at **5, 10 and 15** ft downstream of mixer.

Figure VS-1 – Operating Conditions for Induction Mixer Verification

Rhodamine WT tracer was used as the injection tracer. A stock injection solution of the tracer was prepared by serial dilution of 20% commercial solution with distilled water. The injected tracer rate and concentration were selected such that a mixed concentration at the sampling rig location of approximately 10 ppb to 20 ppb was achieved.

The sampling rig had 25 withdrawal ports located equally spaced across the 7 ft x 7 ft cross-section. Only one downstream position was sampled at a time, and provisions were made for locating and moving the sampling rig so that only one sampling rig would be in the flume channel at one time. Samples from the 25 suction tubes were drawn at approximately equal flow rates for about 10 to 12 minutes. This continuous sampling time was adequate to produce a time average or typical concentration reading. Each of the 25 samples was then analyzed for concentration of tracer using a laboratory-calibrated fluorometer.

The tracer dye concentration at each of the 25 sampling ports throughout the cross section of the flume allowed for the development of isopleth diagrams that were used to demonstrate the extent and uniformity of the chemical plume. Figure VS-2 shows an example of a concentration isopleth diagram.

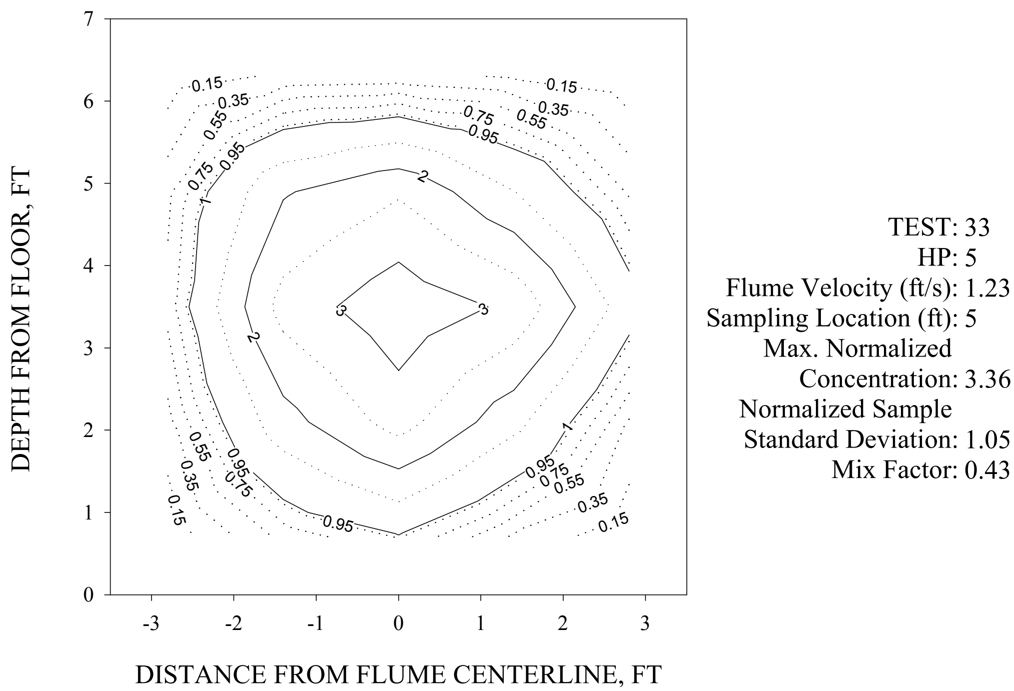

Figure VS-2 – Example of Normalized Concentration Distribution Isopleth Diagram

The isopleth diagrams were prepared for each test condition using normalized concentration values. The measured tracer concentration at each cross-section was normalized by dividing the measured concentration by the uniform concentration (C_u) (where C_u is the tracer concentration), if the tracer was equally dispersed throughout the cross-section of the flume. Thus, a normalized concentration of 1.0 means that the theoretical targeted concentration has been achieved. The performance of the induction mixers was interpreted from these isopleth diagrams.

VERIFICATION OF PERFORMANCE

The mixers produced a roughly circular plume with higher concentrations in the center. Smaller plume areas and higher peak concentrations were observed under the higher flow velocity conditions. In other words, as the energy imparted by the mixer became smaller in relation to the kinetic energy of the flow in the flume (related to flow velocity), the level of mixing observed also lessened. At the lowest flume velocity (0.5 ft/s), the tracer concentrations were more evenly distributed across the flume cross-section and approached a uniform mix, as the plume was able to spread rapidly.

The normalized concentration values and the corresponding isopleth diagrams were used to generate the numerical performance indicators for each of the induction mixers. These indicators are described below and the results are presented in Table VS-1.

A mix factor, F, was calculated for each test using the isopleth diagram. The mix factor indicates the percentage of the total cross-sectional flume channel area that experienced a theoretical complete mix (i.e. equal dye concentration throughout the entire cross-sectional area). By definition, a mix factor of 1 (or 100%) indicates that complete theoretical mixing has occurred. The mix factor provides insight into the area affected by a concentration of chemical greater than the theoretical uniform concentration. In general, the channel area affected by the mixer increased as horsepower increased and decreased as flow velocity increased. For example, as presented in Table VS-1, at 10 ft downstream of the mixer and a flume velocity of 0.5 ft/s the 5 HP mixer affected 68% of the channel area whereas the 20 HP mixer affected 84%. Additionally, when considering the 5 HP mixer at the 10-ft downstream sampling location, the area affected at a flume velocity of 0.5 ft/s was 68% as compared to only 35% at 3.0 ft/s.

The maximum (peak) normalized concentration is the highest concentration of tracer dye observed within the plume, which generally occurred in the center of the channel, closest to the point of injection. The maximum normalized concentration is an indicator of the uniformity of the plume concentrations produced by the mixer. This factor is important because it is possible to have two sets of plume data with similar mix factors but with substantially different maximum concentrations. For example, the 5 HP mixer at the 3.0 ft/s flume velocity at the 10-ft and 15-ft downstream sampling location had approximately equal mix factors of 0.35. With no further information, this could lead to an erroneous conclusion that the plume does not spread as it moves downstream away from the mixer. The maximum normalized concentrations from the two sets of data, however, reveal that the plume is in fact continuing to disperse as it moves downstream, with the maximum value decreasing from 7.14 times to 5.11 times the theoretical average as it moves from 10 ft downstream to 15 ft downstream.

The standard deviation of the normalized dye concentrations at each sampling location characterizes the uniformity of plume concentrations produced by the mixer. The standard deviation is the mathematical expression of the variation of chemical concentration around the average concentration. More uniform mixing is represented by smaller standard deviations. A standard deviation of 0.0 would represent complete uniformity of mixing. Similar to the mix factor trend, uniformity of the chemical concentration within the plume increased as mixer HP increased and decreased as the flow velocity increased.

Table VS-1 below provides a summary of the mix factor, maximum normalized concentration, and standard deviation for the three induction mixers at each of the three flume velocity conditions.

Table VS-1 Summary of Numerical Performance Indicators

	5 ft downstream of Mixer			10 ft downstream of Mixer			15 ft downstream of Mixer		
	5 HP	10 HP	20 HP	5 HP	10 HP	20 HP	5 HP	10 HP	20 HP
Flume Velocity 0.5 ft/s									
Mix Factor, F	0.65	0.77	0.74	0.68	0.80	0.84	0.68	0.76	0.92
Maximum Normalized Concentration	1.64	1.21	1.14	1.32	1.10	1.04	1.16	1.07	1.00
Standard Deviation	0.33	0.09	0.07	0.17	0.05	0.03	0.10	0.04	0.05
Flume Velocity 1.25 ft/s									
Mix Factor, F	0.43	0.62	0.79	0.49	0.69	0.86	0.46	0.69	0.92
Maximum Normalized Concentration	3.33	1.78	1.39	2.55	1.42	1.19	2.07	1.24	1.10
Standard Deviation	1.04	0.42	0.17	0.74	0.24	0.09	0.54	0.16	0.05
Flume Velocity 3.0 ft/s									
Mix Factor, F	0.28	0.37	0.44	0.35	0.38	0.46	0.36	0.39	0.46
Maximum Normalized Concentration	10.75	5.88	3.30	7.14	4.19	2.50	5.11	3.40	2.09
Standard Deviation	2.31	1.64	1.00	1.80	1.26	0.70	1.48	1.04	0.54

Mean velocity gradient (G) is a measure of mixing intensity and has become an industry standard for representing the fluid dynamics of mixing. The G number gives an indication of turbulence as it relates to head loss, which in turn relates to mixing, and is a therefore a parameter of disinfection efficiency. The mean velocity gradient for a typical well-designed diffuser grid system is on the order of 200-500/sec. Research indicates that a G number between 700 and 1,000/sec may be appropriate for disinfection (White, 1992). For the purposes of the verification testing, the mean velocity gradient is used to gauge whether a particular sized induction mixer at a particular velocity is capable of providing mixing adequate for disinfection.

In order to calculate the mean velocity gradient, a minimum affected volume of process water must be calculated. The method used to define the affected volume in the open channel during verification testing was to define the downstream boundary of the channel length beyond which the mix factor ceased to improve by more than five percent. This criterion was made on the assumption that the energy imparted by the mixer had a less significant role in mixing than the energy imparted by the kinetic energy of the flowing process water.

By determining the smallest size of mixer that results in sufficient mixing, an appropriate ratio of horsepower to flow (MGD) can be established. The following criteria were used to assess if sufficient mixing was provided for disinfection of wet-weather flow process water for the purposes of verification testing:

- The standard deviation for the mixing zone was less than 0.5, and consequently the maximum normalized concentration of the tracer was not significantly more than twice the normalized mixer concentration, which suggested the energy imparted by the mixer dispersed disinfectant effectively across the cross-sectional area;

- The mix factor ceased to improve by more than five percent, which suggested the energy imparted by the mixer dispersed disinfectant more aggressively than the kinetic energy of the flow of process water, which defines an affected volume of disinfected water from which to calculate the mean velocity gradient; and,

- The mean velocity gradient (G) is close to, if not greater than, 700/sec within the minimum established volume of water, which can assist in determining an appropriately sized motor for a particular application.

The following is a summary of the verification tests in which a sufficient mixing criteria was achieved, and the correlating power to process water volume ratio:

- The 5 HP mixer provided sufficient mixing at a flume velocity of 0.5 ft/s within the 7 ft x 7 ft open channel five feet downstream of the mixer. The 5 HP unit failed to provide sufficient mixing at flume velocities greater than 0.5 ft/s. This equates to a horsepower to MGD ratio of 0.31.

- The 10 HP mixer provided sufficient mixing at flume velocities of 0.5 ft/s and 1.25 ft/s within the 7 ft x 7 ft open channel five feet downstream of the mixer. This equates to a minimum horsepower to MGD ratio of 0.26.

- The 10 HP mixer provided sufficient mixing at a flume velocity of 3.0 ft/s within a plume-delineated mixing zone 5.5 ft in diameter, 15 feet downstream of the mixer, but did not achieve uniform mixing within the entire 7 ft x 7 ft open channel. This equates to a minimum horsepower to MGD ratio of 0.22.

- The 20 HP mixer provided sufficient mixing at flume velocities of 0.5 ft/s within the 7 ft x 7 ft open channel 10 feet downstream from the mixer, and the 1.2 ft/s flume within the 7 ft x 7 ft open channel five feet downstream from the mixer. The 20 HP marginally failed to provide adequate mixing at 3.0 ft/s within five feet downstream of the mixer. This equates to a minimum horsepower to MGD ratio of 0.28.

In summary, the data indicated a mixer sizing criteria of between 0.22 and 0.31 HP/MGD resulted in mixing sufficient for disinfection for mixing applications in the 7 ft x 7 ft open channel with flow velocities between 0.5 and 3.0 ft/s. The data also indicated a break point in the data at a flow velocity of 1.25 ft/s, where at higher velocities the influence of higher horsepower on the size of the mixing zone volume has diminishing returns. It is clear that flow velocity significantly influences the ability of the mixers to effectively disperse tracer. Therefore, expected range of flow velocities must be considered when selecting an appropriately sized mixer during the design of open channel mixing facilities.

Original Signed by *E. Timothy Oppelt* *9/27/02*	*Original Signed by* *Gordon Bellen* *9/27/02*
E. Timothy Oppelt Director National Risk Management Research Laboratory Office of Research and Development United States Environmental Protection Agency	Gordon Bellen Vice President, Federal Programs NSF International

NOTICE: Verifications are based on an evaluation of technology performance under specific, predetermined criteria and the appropriate quality assurance procedures. EPA and NSF make no expressed or implied warranties as to the performance of the technology and do not certify that a technology will always operate as verified. The end user is solely responsible for complying with any and all applicable federal, state, and local requirements. Mention of corporate names, trade names, or commercial products does not constitute endorsement or recommendation for use of specific products. This report is not a NSF Certification of the specific product mentioned herein.

Availability of Supporting Documents

Copies of the *ETV Protocol for Equipment Verification Testing Induction Mixers Used for High Rate Disnfection of Wet Weather Flows* dated July, 2001, the Verification Statement, and the Verification Report (NSF Report #02/01/EPAWW399) are available from the following sources:

(NOTE: Appendices are not included in the Verification Report. Appendices are available from NSF upon request.)

1. Water Quality Protection Center ETV Program Manager (order hard copy)
   NSF International
   P.O. Box 130140
   Ann Arbor, Michigan 48113-0140
2. NSF web site: http://www.nsf.org/etv (electronic copy)
3. EPA web site: http://www.epa.gov/etv (electronic copy)

Environmental Technology Verification Report

Performance of Induction Mixers for Disinfection of Wet Weather Flows

USFilter/Stranco Products
Water Champ® F Series Chemical Induction System

Prepared for:

NSF International
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With a supplemental text prepared by:

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Under a cooperative agreement with the U.S. Environmental Protection Agency

Mary K. Stinson, Project Officer
National Risk Management Research Laboratory
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Notice

The U.S. Environmental Protection Agency (USEPA) through its Office of Research and Development has financially supported and collaborated with NSF International (NSF) under Cooperative Agreement No. CR825712-01-0. The Wet Weather Flow Technologies Pilot operating under the Environmental Technology Verification (ETV) Program supported this verification effort. This document has been peer reviewed and reviewed by NSF and USEPA and recommended for public release.

Foreword

The following is the final report on an Environmental Technology Verification (ETV) test performed for the NSF International (NSF) and the United States Environmental Protection Agency (USEPA) by Alden Research Laboratory, Inc., in cooperation with USFilter/Stranco Products. The test was conducted in November 2000 at the S.O. Conte Anadromous Fish Research Center, a United States Geological Survey Facility in Turners Falls, Massachusetts. Testing was conducted in accordance with the ETV Verification Protocol for Induction Mixers Used for High Rate Disinfection of Wet Weather Flows, June 2000, developed for the Wet Weather Flow Technologies ETV Pilot under the guidance of the ETV Technology Panel on High Rate Disinfection.

Throughout its history, the USEPA has evaluated the effectiveness of innovative technologies to protect human health and the environment. A new USEPA program, the Environmental Technology Verification Program (ETV) has been instituted to verify the performance of innovative technical solutions to environmental pollution or human health threats. ETV was created to substantially accelerate the entrance of new environmental technologies into the domestic and international marketplace. Verifiable, high quality data on the performance of new technologies is made available to regulators, developers, consulting engineers, and those in the public health and environmental protection industries. This encourages development of new approaches to protect the environment.

The USEPA has partnered with NSF, an independent, not-for-profit testing and certification organization dedicated to public health, safety and protection of the environment, to verify performance of wet weather flow technologies under the Wet Weather Flow Technologies ETV Pilot (WWF Pilot). A goal of verification testing is to enhance and facilitate the acceptance of innovative and effective technologies by regulatory officials and consulting engineers while reducing the need for testing of equipment at each location where the equipment's use is contemplated. NSF will meet this goal by working with manufacturers and NSF-qualified Field Testing Organizations (FTO) to conduct verification testing under the approved protocols.

NSF is conducting the WWF Pilot with participation of manufacturers, under the sponsorship of the USEPA Office of Research and Development, National Risk Management Research Laboratory, Urban Watershed Management Branch, Edison, New Jersey. It is important to note that verification of the equipment does not mean that the equipment is "certified" by NSF or "accepted" by USEPA. Rather, it recognizes that the performance of the equipment has been evaluated by these organizations in accordance with an established Verification Protocol and that objective performance data is available.

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Abbreviations and Acronyms

ARL	Alden Research Laboratory, Inc.
CAFRC	S.O. Conte Anadromous Fish Research Center
CSO	combined sewer overflow
USEPA	United States Environmental Protection Agency
ETV	Environmental Technology Verification Program
ft	foot (or feet)
FTO	Field Testing Organization
G	mean velocity gradient
gpm	gallons per minute
HP	horsepower
MGD	million gallons per day
ml	milliliter
NSF	NSF International, formerly known as National Sanitation Foundation
ppb	parts per billion
RMS	root mean square
RPM	rotations per minute
sec	second
USF	US Filter/Stranco Products
USGS	United States Geological Survey
VTP	Verification Test Plan
WWF	Wet Weather Flow
WWF Pilot	Wet Weather Flow Technologies ETV Pilot

Acknowledgments

The Field Testing Organization, Alden Research Laboratory, was responsible for all elements in the testing sequence, including design of the test flume and sampling rig, calibration and verification of instruments, data collection and analysis, data management, data interpretation and the preparation of this report.

Alden Research Laboratory, Inc.
30 Shrewsbury Street
Holden, MA 01520
Contact Person: Dr. M. Padmanabhan and Mr. Philip Stacy

Moffa & Associates, A Unit of Brown & Caldwell, Syracuse, New York provided technical guidance and documentation review during various stages of this verification. Moffa & Associates also provided supplemental text for this Verification Report on the use of induction mixing systems in treating wet weather flows and the potential applications of the data contained in this Verification Report.

All testing and sample analysis was conducted under the direction of Alden Research Laboratory at:

S.O. Conte Anadromous Fish Research Center (CAFRC)
One Migratory Way
PO Box 796
Turners Falls, MA 01376
Contact Person: Mr. John Noreika

CAFRC is a USGS Facility, without which the testing would not have been possible. The staff at CAFRC was instrumental in establishing and maintaining the required test conditions, including the flume dimensions, flows, flow velocities, and electrical power needs.

The Manufacturer of the Equipment was:

USFilter/Stranco Products
595 Industrial Drive
Bradley, IL 60915
Contact Person: Mr. James Marcukaitis, Product Manager

1 Introduction

1.1 Environmental Technology Verification Program

The U.S. Environmental Protection Agency (USEPA) created the Environmental Technology Verification (ETV) Program to facilitate the deployment of innovative or improved environmental technologies through performance verification and dissemination of information. The goal of the ETV program is to further environmental protection by substantially accelerating the acceptance and use of improved, cost-effective technologies. ETV seeks to achieve this goal by providing high quality, peer reviewed data on technology performance to those involved in the design, distribution, permitting, purchase, and use of environmental technologies.

ETV works in partnership with recognized standards and testing organizations; stakeholders groups which consist of buyers, vendor organizations, and permitters; and with the full participation of individual technology developers. The program evaluates the performance of innovative technologies by developing test plans that are responsive to the needs of stakeholders, conducting field and/or laboratory testing, collecting and analyzing data, and preparing peer reviewed reports. All evaluations are conducted in accordance with rigorous quality assurance protocols to ensure that data of known and adequate quality are generated and that the results are defensible.

NSF International (NSF) in cooperation with the USEPA operates the Wet Weather Flow Technologies Pilot (WWF Pilot). The WWF Pilot evaluated the performance of USFilter/Stranco Products Water Champ® F Series Chemical Induction System, a mixing technology whose many uses include the rapid mixing of chemical disinfectants for the treatment of wastewater and combined sewer flows. The objective of verification was to characterize the ability of the system to rapidly transfer a chemical into a flowing body of water by measuring the uniformity of chemical concentrations over measured portions of the flow cross-section at various distances downstream from the mixer. Testing was conducted in accordance with the June 2000 version of the Generic Verification Protocol for Induction Mixers Used for High Rate Disinfection of Wet Weather Flow.

1.2 Scope of Induction Mixer Verification

The WWF Pilot developed a program for the verification of induction mixers intended for use in the chemical disinfection of wet weather flows, such as combined sewer overflows and sanitary sewer overflows. The objective of the verification is to evaluate the performance of induction mixers with respect to their ability to transfer chemicals into the process water. The volume of water affected by a mixer, herein referred to as the mixing zone, was used to portray the performance of each mixer. The velocity of the process water and the size of the mixer (i.e. horsepower) have the greatest influence on the induction mixer's ability to transfer chemicals into the water. Therefore a series of different size mixers were tested over a range of flow velocities. These mixers sizes and velocities were representative of typical installations at wet-weather treatment facilities.

The scope of each verification test was to define the mixing zone volume by introducing a conservative dye at the point of the impeller and measuring the dye downstream the impeller. The measured dye was then used to define the volume of water affected by the mixer. These tests were performed at a hydraulic laboratory for a combination of different mixer sizes, flow velocities and mixing times.

The transfer of chemicals into the process water is a function of mechanical dispersion and molecular diffusion. In the case of induction mixers, the mechanical dispersion is several orders of magnitude greater than molecular diffusion, and therefore molecular diffusion was not accounted for in these verification tests. The mechanical dispersion is a function of the energy imparted by the mixer and the energy imparted by the velocity of the process water. The difference between the active mixing of the induction mixer and the passive mixing of the process water velocity is addressed.

1.3 Testing Participants and Responsibilities

The ETV testing of the Water Champ® Series F Chemical Induction System was a cooperative effort between the following participants:

- NSF International (NSF)
- Alden Research Laboratory, Inc. (ARL)
- USFilter/Stranco Products (USF)
- USGS S.O. Conte Anadromous Fish Research Center (CAFRC)
- U.S. Environmental Protection Agency (USEPA)

The following is a brief description of each ETV participant and their roles and responsibilities.

1.3.1 NSF International

As the Verification Partner for the USEPA's Wet Weather Flow Technologies Pilot, NSF provided administrative and quality assurance oversight of the verification process. NSF was responsible for the selection of the Field Testing Organization (FTO). NSF coordinated the review and approval of the Verification Test Plan (VTP) and this Verification Report. NSF personnel conducted an audit of the testing facilities and operations at CAFRC prior to the start of testing.

1.3.2 Field Testing Organization

ARL, an independent testing and research organization, conducted the verification testing of the Water Champ® Chemical Induction System. The primary responsibilities of ARL included:

- Preparation of a VTP, including revisions in response to review comments;
- Coordination with the manufacturer (vendor) of the mixers tested;
- Implementation of the approved VTP;
- Providing logistical support for establishing a communication network and scheduling and coordinating the activities for the verification testing;

- Overseeing and conducting the testing in accordance with this VTP;
- Managing, evaluating, interpreting and reporting of data generated during the testing;
- Providing all data generated during testing in electronic and hard copy format; and
- Preparation of Verification Report.

ARL employees conducted the onsite analyses and data recording during the testing. Mr. Phil Stacy, ARL Project Engineer managed the on-site operations and oversight of the daily testing activities.

1.3.3 Manufacturer

USF manufactured the tested mixers. USF supplied three submersible chemical mixers (5 HP, 10 HP, and 20 HP) and the necessary mounting hardware, chemical feed lines and other ancillary equipment needed for their operation. A list of any special requirements, limitations and instructions was also provided, as well as descriptive details about the capabilities and intended function of the mixers. The manufacturer maintained communication with ARL to insure on time delivery of all equipment, consistent with the schedule in the VTP. A representative of USF was on site for two of the four days during which testing was conducted. He provided guidance to FTO personnel on the proper installation and operation of the mixers.

1.3.4 Test site

Verification tests were conducted using a large test flume at the CAFRC facility in Turners Falls, Massachusetts. CAFRC is a United States Geological Survey (USGS) Facility where research and equipment testing is conducted on a regular basis. CAFRC has previously participated in the testing of high rate induction mixers and has large indoor flumes and flow capacity of about 150 ft^3/sec, which are uniquely suited for this purpose.

The CAFRC personnel had the following responsibilities:

- Modifying the existing test flume to provide the required dimensions and features;
- Providing steady flow to achieve the required velocities;
- Measuring, evaluating and reporting velocities and flows established during testing;
- Providing the needed electrical power for the mixers and sampling equipment;
- Assisting with installation and repositioning of the sampling rig; and
- Providing any needed QA/QC documentation for the flow and velocities.

1.3.5 U.S. Environmental Protection Agency

The USEPA's National Risk Management Research Laboratory (NRMRL) provides administrative, technical and quality assurance guidance and oversight on all WWF pilot activities. USEPA personnel were responsible for:

- Review and approval of the VTP;
- Review and approval of the Verification Report;
- Review and approval of the Verification Statement; and

- Posting of the Verification Report and Statement on the USEPA website.

1.4 Chemical Disinfection of Wet Weather Flows

Disinfection of wet-weather flow (WWF) discharges is generally practiced to control the discharge of pathogens and other microorganisms into receiving waters. The disinfection of WWF can present challenges because of their intermittent nature, variable and high flow rate, wide temperature variation, and variable water quality.

A number of studies published in the 1970s investigated how effective bacterial kills may be achieved at lower contact times by using increased mixing intensity, increased disinfectant dose, and alternate chemicals having a higher oxidation rate than chlorine, or a combination thereof (Crane Co. 1970, Moffa, Tifft and Richardson 1975, Geisser and Garver 1977, Tift et al. 1977, USEPA 1973a,b, 1975, 1979a,b). These methods are generally refereed to as "high-rate disinfection". There has been no clear definition as to what constitutes high-rate disinfection other than achieving the required bacterial reductions at detention times less than 15 to 30 minutes (USEPA 1993).

Disinfection is generally governed by the following relationship:

$$\text{Kill} = c \times t \qquad (1\text{-}1)$$

Where:

c = concentration of disinfectant
t = time of contact (within a contained volume)

However, to identify the benefits of intense mixing, this relationship was expanded to include a factor for mixing intensity, which is herein referred to as "G". Disinfection processes that use mechanical mixing are generally governed by the following relationship:

$$\text{Kill} = c \times G \times t \qquad (1\text{-}2)$$

Where:

G = mixing intensity
c = concentration of disinfectant
t = time of contact (within a contained volume)

The mixing intensity is a function of the power imparted into a volume of water. Mean velocity gradient (G) is a measure of mixing intensity and has become an industry standard for representing the fluid mechanics of mixing. It is directly related to the total shear per unit volume per unit of time. The G number gives an indication of turbulence as it relates to head loss, which in turn relates to mixing (White, 1992). The mean velocity gradient is therefore a parameter of disinfection efficiency. G can be expressed by the following equation:

$$G = ((P \times C_f) / (u \times V))^{1/2} \qquad (1\text{-}3)$$

Where:

P = power requirement (HP)
V = volume of affected process water (ft^3)
u = absolute fluid viscosity (lb•sec/ft^2)
C_f= conversion factor (550 ft•lb/sec/HP)

The mean velocity gradient for a typical well designed diffuser grid system is on the order of 200-500/sec. Research by White (1992) indicates that a G number between 700 and 1,000/sec may be appropriate for disinfection mixing regardless of disinfection requirements.

Collins and Kruse (USEPA 1973a) demonstrated the influence of mixing intensity on bacterial kills and formation of chloramines with Cl_2. When chlorine or hypochlorite is added to wastewater containing ammonia, the free chlorine will react to form chloramines. The rate of bactericidal efficacy of chloramines is significantly less than that of free chlorine. It is theorized that by instantaneously dispersing hypochlorite in the wastewater stream using high-rate mixing, more of the organisms in the wastewater are subjected to chlorine in its free form prior to the formation of chloramines and, therefore, resulting in greater kills.

1.5 The Use of Mechanical Induction Mixers in WWF Applications

Use of induction mixers as compared to other mixing techniques, such as diffusers and paddle mixers, reduces power and chemical consumption and therefore annual operation and maintenance costs (White 1992, Diaz 2001). Additionally, experience has shown that the long contact time required for conventional wastewater treatment is extremely costly for the treatment of WWF due to the magnitude of peak flow rates that occur on an infrequent basis. However, disinfection of WWF can be achieved at shorter contact times by providing intense mixing and an increased disinfection dosage to ensure disinfectant contact with the maximum number of microorganisms (Benjes 1976). Reduced contact tank volume can significantly reduce the capital cost associated with constructing a WWF disinfection facility.

The mechanical induction mixer is fairly simple in construction. The major elements are illustrated in Figure1-1. In general, a submersible motor rotates a shaft on which an impeller is mounted. The impeller rotates at a speed greater than 3,000 RPM within a housing that encompasses the impeller. The impeller and housing is similar in concept to a submersible pump in that the rotating impeller within a confined volume creates a negative pressure. This negative pressure is used to draw or induct flow through the chemical induction port.

The induction capability of the induction mixers is not typically utilized in WWF applications because of the extreme variation in flow rates characteristic of a WWF treatment facility. As described above, the chemical is inducted into the impeller housing by the negative pressure produced by the rotating impeller, which remains relatively constant during the operation of the mixer. This means the induction rate (i.e. disinfection feed rate) is relatively constant during operations. This is not appropriate for WWF disinfection facilities because this disinfection feed rate needs to be paced to correspond with the highly variable WWF rate to provide a constant disinfection dose (i.e. $Q_1 \times C_1 = Q_2 \times C_2$). For example, throughout the duration of a WWF event, flows processed by a single 20-HP mixer can range from 1 ft^3/sec to 220 ft^3/sec. Therefore, the disinfectant feed rate must also vary in order to maintain a constant disinfectant dose. Disinfection feed rates with such a wide range are typically provided by a series of variable speed feed pumps controlled by flow sensors in the influent to the treatment facility. These feed pumps negate the need for the induction capabilities of the mixers. However, the high rpm and the resulting energy it imparts into the WWF to disperse chemical is very important for the efficient use of the disinfectant in a "high-rate disinfection" application.

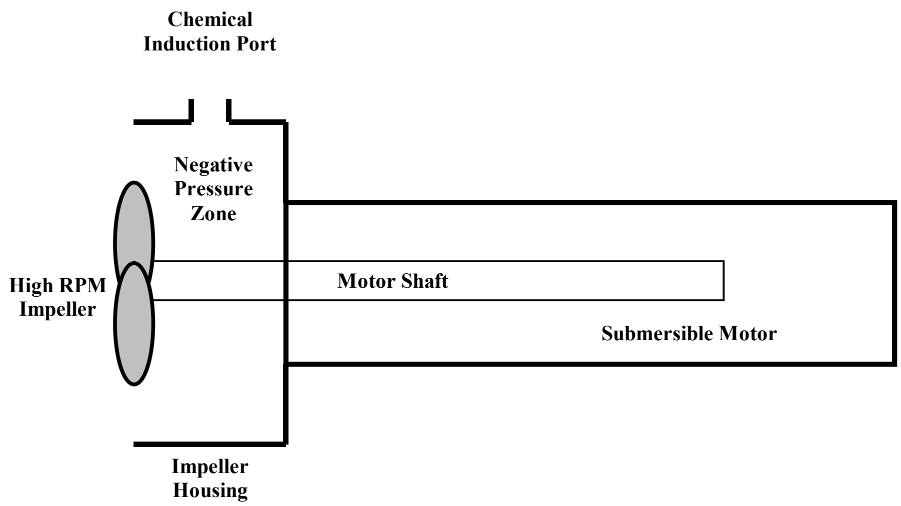


Figure 1-1: Typical Induction Mixer

1.6 Verification Objectives

In the past, researchers have related bacterial reductions to the parameters G and t (USEPA 1973a,b, 1975, 1979a,b). This relationship holds true when the mixing devices are operated in a mixing chamber of fixed size. This relationship does not necessarily hold true when the mixing devices are operated in an open channel, allowing the mixing zone volume to change as a result of mixer horsepower, channel geometry, and or flow velocity. As such White (1992) stated that the subject of mixing intensity as it relates to disinfection efficiency needs more research and laboratory study of the fluid mechanics of mixing the chemical with wastewater. The objective would be to quantify intensity versus homogeneity of the mixture in a given time frame.

Manufacturers of induction mixers have made claims about the mixing capabilities of their product and their ability to provide rapid, uniform chemical transfer resulting in reduction or elimination of chemical breakout and stratification. Since these claims are subjective, manufacturers will often provide a G factor for each specific induction mixer installation. However, in some installations, e.g., an open channel, there is no standard method or approach used for calculating this G factor. As presented in Section 1.4, G is a function of the mixer power, fluid viscosity, and the volume of the affected process water. The power and viscosity variables are standard and therefore the manufacturers use consistent values, but each manufacturer defines the process water volume differently. As a result each manufacturer may claim a different G for the same application, based on their definition of volume. Additionally, a high G value (G> 700/sec) has generally implied a homogenous dispersion of chemical, but this is not well documented especially in an open channel application where flow velocities can vary throughout a WWF event.

Data collected in accordance with the ETV Protocol can be used to determine the volume of process water affected by the induction mixer, or mixing volume, and to characterize the uniformity of chemical concentrations within the mixing volume.

The verification testing was performed in a hydraulic laboratory, during which the induction mixers were operated as though installed in an open-channel of a WWF disinfection facility. However, instead of mixing a chemical disinfectant into the process water, a conservative tracer was used, which allowed the researchers to observe the extent of mixing provided by the mixers. The conservative tracer (Rhodamine WT) was used as a surrogate to a disinfection chemical such as chlorine because it was easier and more accurate to measure.

In practice, a disinfection chemical such as chlorine is not conservative in that it reacts with other chemicals to form a variety of different compounds. For example, when sodium hypochlorite is injected into a wastewater for the purpose of disinfection, it instantaneously dissociates into hypochlorous acid and hypochlorite ion. These compounds in turn react and form other compounds such as chloramines and other chlorinated compounds. Therefore, many species of chlorine including reactive and inert forms exist throughout the mixing zone affected by the mixer. However, disinfection facilities are designed to provide for residual chlorine to ensure that the chemical demand is exceeded. Therefore, it can be assumed that in a properly designed and operated disinfection facility there is sufficient chlorine in its various forms being applied to reach the boundaries of the mixing volume.

Conducting the verification testing in a hydraulic laboratory also provided the researchers with the ability to operate and evaluate the mixers under different flow velocities. The flow velocity influences the ability of the mixer to disperse chemical in two ways; both of which relate to the kinetic energy of the process water. The first is that a higher flow velocity represents a higher kinetic energy, which reduces the mixer's ability to disperse the chemical. The second is that a higher flow velocity creates greater turbulence, and in some cases the turbulence may be so great that a mixer is not required at all (i.e. passive mixing, which is not covered in this Verification Report). These are conflicting statements; but depending upon site-specific conditions, flow velocity may or may not improve mixing. For example, in a hydraulic laboratory setting, turbulence can be minimized by the use of hydraulic apparatus, and therefore passive mixing is minimized, which was the case in this verification testing. However, in a wet-weather disinfection facility where there may be hydraulic bends and drops, turbulence could play a significant role in mixing.

2 Equipment Description and Operating Processes

2.1 General Description

U.S. Filter/Stranco provided three submersible Water Champ® F Series induction mixers nominally rated at 5 HP, 10 HP, and 20 HP. The mixers were typical of the product line, and no special provisions or changes were made to the mixers. All mixers were powered electrically at 460 VAC, 3 phase using the standard power cable. The manufacturer provided a line for the induction flow, and an orifice plate flow meter assembly was added by ARL as part of the test equipment. Drawings, photographs, and specifications provided by USF, including the geometry of the propeller tested for each mixer, are included as Appendix A.

The principle of operation is that rotation of the uniquely shaped propeller causes a reduction in pressure in the chamber surrounding the impeller shaft. Connecting a flow line to the port in the chamber causes flow to be induced. This flow is propelled outward by the rotating propeller and mixed vigorously with the surrounding water (flow).

2.2 Water Champ® F Series Specifications

The 20 HP mixer had the Model designation of SWC20F and had a maximum liquid induction flow of 60 gpm. The 10 HP was designated as SWC10F and had a maximum liquid induction flow of 40 gpm. The 5 HP was designated as SWC5F and had a maximum liquid induction flow of 25 gpm. The speed of all units was 3,450 rpm. The propeller geometries for each size mixer are shown in Appendix A.

The submersible F Series offers high quality design and construction, the motor being hermetically sealed 316 stainless steel and most wetted materials being constructed from Grade 2 Titanium (unalloyed). A mounting is configured for open channel applications and can be retrofitted to basins and tanks. Mixers can be oriented in either horizontal or vertical position depending upon the hydraulic constraints and designer preference. For these tests, based on installation considerations, horizontal orientation was used, with the propeller pointed upstream into the flowing water.

2.3 Operating Requirements

The mixer was submerged at least 18 inches at all times. All power supplies were locked out when performing any maintenance to the system.

2.4 Mixer Flow (Disinfection Feed Rate)

The specification for mixer flow, or disinfection feed rate, for each mixer size (HP) can vary depending on the mixer application. The appropriate disinfection feed rates for each size mixer were established in the VTP in consultation with Moffa & Associates. The details are given below.

The disinfectant feed rate (Q_c) to an induction mixer is a function of the:

- Wastewater flow (Q_f),
- Disinfectant feed concentration (C_c), and
- Required disinfectant dose (C_f).

Additionally, the mixer horsepower is related to the wastewater flow; a typical mixer sizing criteria for CSO applications (per the manufacturer or vendor) is 0.14 HP/MGD (Moffa & Associates, 1999). Therefore, the proposed mixer sizes for the verification testing and their associated wastewater design flows are:

- 5 HP for 35 MGD
- 10 HP for 70 MGD
- 20 HP for 140 MGD

A mass balance equation was used to estimate the disinfectant feed rates or mixer flow based on the mixer horsepower and design wastewater flows listed above.

$$Q_f \times C_f = Q_c \times C_c \tag{2-1}$$

Assuming a 7.5% sodium hypochlorite feed (injected) concentration (C_c) and a final mixed dose of 20 mg/l (C_f) in the wastewater flow, solving for Q_c (the required mixer flow or disinfectant feed rate) yields the mixer flows shown in Table 2-1.

Table 2-1: Tracer Feed Rates

Q_f, MGD	Mixer Size HP	Mixer Flow (Disinfectant /Tracer Feed Rate), gpm
35	5	7
70	10	13
140	20	26

3 Description of Hydraulic Test Facility

3.1 Test Location

The CAFRC is situated in the town of Turners Falls, Massachusetts, on bank of a canal to the Cabot Hydroelectric Power Station. Water enters the building containing the test flume from an inlet structure on the bank of the canal. The inlet to a below ground conduit was used for intake flow. Flow from the buried conduit was controlled by a sluice gate in the building. This flow was distributed to a forebay upstream of the test flume by an inlet chamber and floor diffuser.

Testing required the use of only one of the three concrete flumes in the building. Temporary walls, constructed of plywood, narrowed the width of the flume and achieved the dimensions specified in the VTP.

3.2 Test Flume

A rectangular channel section 7 ft wide with a water depth of 7 ft was established for testing. To achieve a relatively uniform velocity distribution at the mixer, the length of the flume upstream of the mixer was 20 ft, and the test channel entrance was rounded to avoid flow separation, as shown in Figure 3-1. Upstream of the test channel entrance, the flow was guided by a straight flume 10 ft wide and 32 ft long, with an upstream flow distributor (see Figure 3-1). The test channel had a once-through flow system drawing water from the power plant canal and discharging the outflow to the canal with no possibility of discharged water re-entering the channel.

The 7-ft wide test flume was extended 28 ft downstream of the mixer before expanding to the wider 10-ft flume width. Using mounting hardware supplied by the manufacturer, the mixer was installed in accordance with the manufacturer’s instruction at the designated location in the test flume

A 25-point water (tracer) sampling rig was positioned at locations 5 ft, 10 ft, and 15 ft downstream from the mixer (impeller). Only one location was sampled at a given time, with provisions made for locating and moving the sampling rig between sampling intervals.

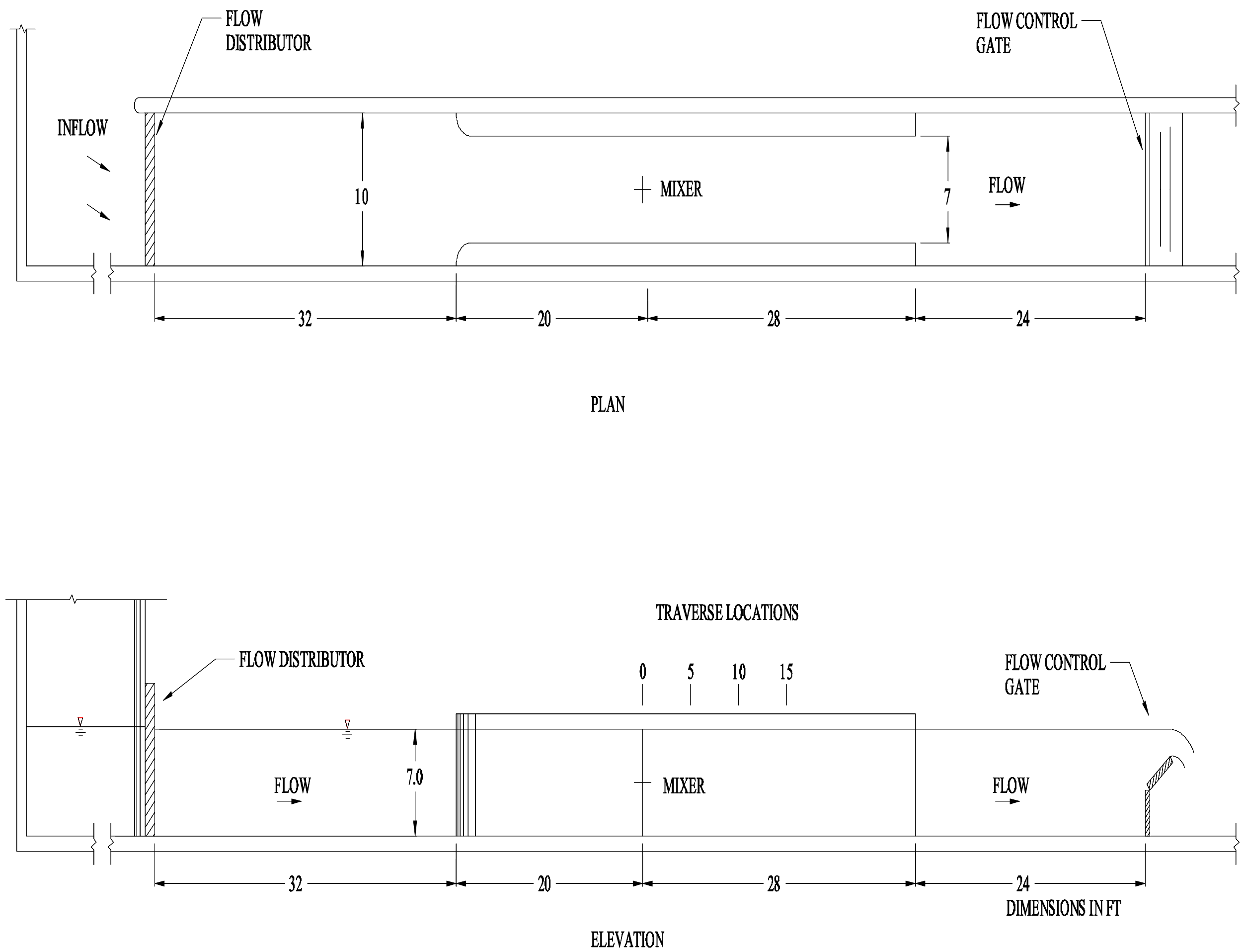


Figure 3-1: Plan And Elevation of Test Setup

3.3 Flume Flow Control

A hinged steel weir controlled flow and water level in the flume. The weir was calibrated prior to initiation of tests to obtain the head-flow relationship of the weir at three positions and the desired water level of 7 ft. The weir was located 24 ft downstream of the end of the test flume so that there were no effects on the flow distribution in the test flume caused by the weir.

The maximum velocity in the flume required by the Verification Protocol was 3 ft/sec. To achieve this velocity, water flows of up to 150 ft^3/sec were supplied to the flume. Lower velocities were set by reducing the inflow with the upstream sluice gate and raising the weir to maintain the desired water level. The flow required for a given test was established by presetting the weir and adjusting the flume inflow until the required depth (7 ft) was achieved. As a part of the weir calibration, the velocity distribution at a 7 ft x 7 ft cross-section just upstream of the mixer location was measured for each flow using a Sontek Acoustic Doppler Velocimeter available at CAFRC. Table 3-1 contains a list of all instruments and equipment used to measure and maintain the required flow conditions. A description of the weir calibration is provided in Appendix B.

Table 3-1: Instrumentation/Equipment List

Variable/Parameter	Instrument Number and Description	
Flume Width	1	Stanley® 25 ft retracting tape measure (or equivalent)
Water Depth	2	UNIDATA™ model 6541/c water level instrument with internal data logger
Weir Position	3	RITTmeyer Angle Transmitter resistive/optical model MGAx
Water Velocity	4	Sontek® ADV three axis velocity probe.
Water (Flume) Temperature	5	Platinum RTD and Omega® digital readout ARL S/N: 0500
Mixer Location	1	Stanley® 25 ft retracting tape measure (or equivalent) reference to flume floor and walls
Mixer Power	6	Fluke® 41B Power Meter
Mixer Flow	7	Orifice Meter Section S/N: 1064
Orifice Meter Manometer	8	Lufkin® 066D 6ft Red End Engineer's Folding Wood Rule
Tracer Injection Concentration	9	Serial Dilution of 20% Stock using Class A pipettes and flasks
Tracer Injection Rate	10	Timed 100 ml Class A pipette (Integral with tracer injection system)
Tracer Injection Timer	11	Newport® Model 6130A Digital Timer (Integral with tracer injection system)
Tracer Injection Temperature	12	Omega® Model 199B platinum RTD (Integral with tracer injection system)
Sample Port Location	1	Stanley® 25 ft retracting tape measure or equivalent Reference to mixer impeller
Sample Concentration	13	Fluorometer; Turner Designs Model 10
Sample Water Temperature	14	Newport® RTD (Integral with fluorometer system)
Fluorometer Filter (light) Temperature	15	Omega® Model 199 Platinum RTD (Integral with fluorometer system)
Fluorometer Calibration	16	Serial Dilution of 2500ppb Stock using Class A pipettes and flasks

3.4 Instrumentation For Tracer Dilution

3.4.1 Tracer Injection

Rhodamine WT was used as the tracer. Rhodamine WT has low adsorption characteristics and is supplied at nominal 20% concentration by weight. Stock injection solutions were prepared at ARL to a concentration of 2 x 10^7 ppb by serial dilution of the supplied solution with distilled water. The injection rate was established for each plume velocity to produce a theoretical (perfect mixing) concentration at the sampling locations of approximately 12 ppb, using the following mass balance equation:

$$C_i \times Q_i = C_t \times Q_t \quad (3\text{-}1)$$

Where

C_i	=	injected tracer concentration
Q_i	=	injected tracer flow
C_t	=	mixed concentration
Q_t	=	mixed flow

Based on experience with mixers of this type, it was expected that the actual flume concentrations could be up to five times greater than the theoretical average. Therefore, it was necessary to establish an injection rate so that the potential highest sample concentration was within the linear response range of the fluorometer, or below approximately 80 ppb. Tracer injection rates of 0.4 ml/s, 1.0 ml/s, and 2.5 ml/s were selected for the three flume velocities of 0.5 ft/sec, 1.25 ft/sec, and 3.0 ft/sec, respectively.

Fluorescence of the tracer is a function of water temperature. Variations from the water temperature during calibration were accounted for by using the following equation:

$$C = C_r \times e^{k \times (Tr - Tc)} \quad (3\text{-}2)$$

Where

C	=	actual concentration (ppb)
C_r	=	apparent concentration at Temperature T_r (ppb)
T_c	=	calibration temperature (EF)
k	=	temperature connection coefficient (1/EF)
T_r	=	water temperature (EF)

The standard temperature coefficient, k, for Rhodamine WT is 0.01444/EF.

3.4.2 Tracer Sampling Rig

A sampling rig with five vertical arrays of sampling ports was fabricated. The sample ports were located at 10%, 30%, 50%, 70%, and 90% of the total depth (center of five equal distances) at a longitudinal spacing selected to generate equal areas of sampling for each port, as shown in Figure 3-2. Thus, the sampling rig had 25 suction tubes across the 7 ft x 7 ft cross-section.

The number of sampling ports deviated from the minimum specified in the Verification Protocol. The 7 ft x 7 ft flume cross-section, which exceeds the minimum cross section of 6 ft x 6 ft recommended in the Verification Protocol, was chosen to improve the experimental design by moving the walls and their potential effects on mixing away from the mixer (NSF, 2000). To adhere to the Verification Protocol requirement of one port per square foot in a 7 ft x 7 ft flume would have required 49 sample bottles. This was considered impractical in terms of the sampling and analysis effort. In previous similar testing of induction mixers, ARL had found that 25 ports with similar spacing (in terms of percent depth and width) were adequate to map the tracer plume within a flume with an even larger cross-section (8 ft x 8 ft and 8 ft x 10 ft). NSF approved this variance from the Verification Protocol prior to the start of testing.

Using individual pumps and valves, a portion of the flow was directed to each of the 25 sample collection bottles while the remainder was returned to the flume. The necessary flow to each sample bottle was obtained by manually adjusting a separate rotameter at each sampling port.

3.4.3 Fluorometer

A Turner Designs Model 10 fluorometer was used to measure tracer concentration. The fluorometer has a minimum detection level of 0.01 ppb. Rhodamine tracer in concentrations below 20 ppb, although undetectable visually, provided sufficient measurement accuracy. Concentration of tracer in the samples was determined by fluorescence intensity, which is proportional to the voltage output of the fluorometer.

The Turner Designs Model 10 fluorometer has multiple settings to increase the range of measurable concentrations. Two settings are available, Xl and Xl00, having a 100 to 1 effect on output. Within each range, the sensitivity may be changed from Xl to X31.6 in four equal steps, having about a 30-fold effect on output. The instrument span and zero offset are also adjustable to match the output to the measured concentration. The fluorometer was set up to read in the upper one-third output of the X1 sensitivity scale to ensure good resolution for a wide concentration range.

A portable computer recorded fluorometer voltage output and water and instrument temperature readings from two Resistance Temperature Detector (RTD) thermometers with a 12-bit analog to digital converter. Full scale on the computer is two volts with a resolution of 0.0005 volt. Transmission characteristics of the primary light filter in the fluorometer change slightly with temperature, affecting instrument sensitivity. Therefore, a platinum resistance temperature sensor was mounted on the filter to monitor the temperature and assure instrument drift was within acceptable limits. A similar temperature sensor, mounted in a 1/8" diameter rod, measured the water sample temperature, which was used to correct measured fluorometer voltage output to calibration water temperature with Equation 3-2. The temperature sensors used to determine the water temperatures at the fluorometer and the tracer injection temperature were calibrated against a NIST traceable thermometer standard. Resolution of the digital temperature sensors was 0.1EF.

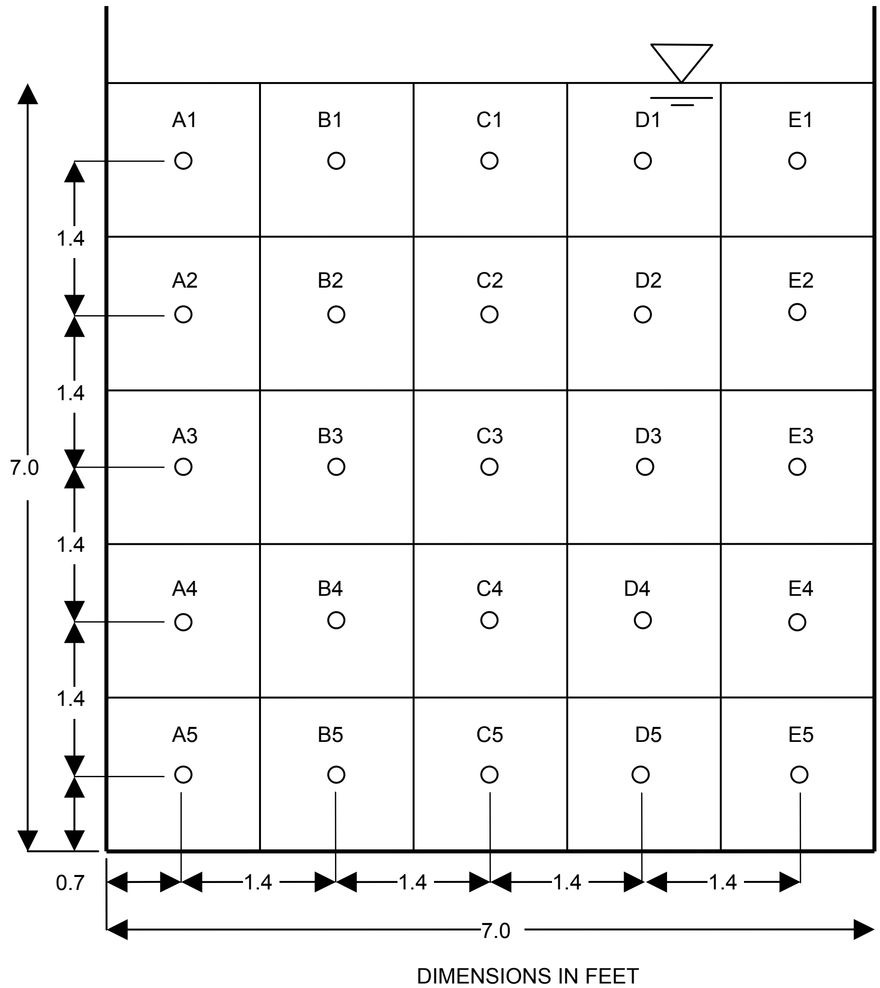


Figure 3-2: Location of Sampling Tubes

4 Methods

4.1 Test Objectives

The objective of this testing was to characterize the performance of high-rate induction mixers manufactured by USF with respect to their ability to rapidly transfer a non-reactive tracer (as a surrogate for a chemical disinfectant) into a flowing body of clean water. Mixer performance was characterized by the degree of tracer uniformity achieved over measured portions of the flow cross-section (the mixing zone) at various distances downstream from the mixer impeller. This characterization was for a range of flow velocities representative of those in wet weather flow collection and treatment facilities.

4.2 Test Series

Three of the USF Water Champ F series mixers (5 HP, 10 HP, and 20HP) were tested. Table 4-1 shows the test matrix employed. Test series A, B, and C correspond to the test series for the 5, 10, and 20 HP mixers, respectively.

Each test series evaluated a single induction mixer under three flow velocities: 0.5 ft/sec, 1.25 ft/sec, and 3.0 ft/sec. The Verification Protocol had called for testing at flow velocities of 0.5 ft/sec, 2.0 ft/sec, and 3.0 ft/sec in order to represent flows typical of a wet weather flow treatment facility. It was agreed during development of the VTP that a 1.25 ft/s velocity would be used in place of the 2.0 ft/sec prescribed in the Verification Protocol to provide a better distribution of data in the 0.5 ft/sec to 3 ft/sec range. Each test series consisted of nine tests and one or two repeats, as shown in the test matrix of Table 4-1.

For each test, the flow velocity was held steady and the water depth was maintained at 7 ft. The cross-sectional mixing was evaluated for each test at one selected flume cross-section by concentration measurements of the 25 samples collected across the cross-section using the described sampling rig. One sampling rig was installed in the channel and was moved to the designated distances of 5 ft, 10 ft, and 15 ft downstream of the mixer, as needed to perform the required sampling.

Two types of repeat tests were included in the test matrix, as shown in Table 4-1. Repeat tests designated as RT-tests in Table 4-1 involved duplicating all sample collection and analysis steps for a given set of test conditions. Repeat tests designated as RA-tests in Table 4-1, only involved repeating the fluorometer analyses of each of the 25 samples collected during a previous test. The test matrix included one RT- test for each of three test series (A, B, and C) and one RA- test for each of the test series A and B.

Table 4-1: Test Matrix

Test Series	Test Number	Mixer (HP)	Flume Velocity (ft/sec)	Distance From Mixer (ft)
A (5 HP)	34	5	0.50	5
	34RT	5	0.50	5
	35	5	0.50	10
	35RA	5	0.50	10
	36	5	0.50	15
	33	5	1.25	5
	32	5	1.25	10
	31	5	1.25	15
	28	5	3.00	5
	29	5	3.00	10
	30	5	3.00	15
B (10 HP)	37	10	0.50	5
	38	10	0.50	10
	39	10	0.50	15
	40	10	1.25	5
	40RT	10	1.25	5
	41	10	1.25	10
	42	10	1.25	15
	43	10	3.00	5
	43RA	10	3.00	5
	44	10	3.00	10
	45	10	3.00	15
C (20 HP)	52RT	20	0.50	5
	52	20	0.50	5
	53	20	0.50	10
	54	20	0.50	15
	51	20	1.25	5
	50	20	1.25	10
	49	20	1.25	15
	46	20	3.00	5
	47	20	3.00	10
	48	20	3.00	15

4.3 Tracer Dilution Procedures

4.3.1 Tracer Injection

Diluted Rhodamine WT tracer solution (stock injection solution prepared by serial dilution of 20% commercial solution with distilled water) was injected into the mixer flow by a constant displacement pump, whose variable stroke controls the tracer injection rate. Figure 4-1 is a schematic of the injection system. The injection pump and a 100 ml pipette with reduced area measuring stations were supplied from a 20-liter Mariotte vessel (a vessel which maintains a constant inlet pressure on the injection pump regardless of liquid level in the vessel).

Tracer injection flow was constant for each test and was measured by the volumetric method. The supply line from the Mariotte vessel was shut off via a valve. Tracer was supplied to the pump solely from a Class A pipette having a volume uncertainty of 0.1%. A digital timer with 0.001-second resolution was started and stopped, as the meniscus of the tracer passed the measuring locations on the pipette. The tracer injection rate was recorded one to two times per test (sample data sheets are included in Appendix B). The tracer injection flow was low (from 0.4 ml/s to 2.5 ml/s) and thus a secondary transport flow was needed. The secondary transport flow was flume water drawn from a location upstream of the mixer using a sump pump. Secondary transport flows of between 2 gpm to 10 gpm were introduced via a tee in the inlet pipe of the pump providing flow to the mixer.

The mixer flow (disinfectant feed rate) was provided by a 2 HP pump, that withdrew flow from the flume approximately 4 ft to 6 ft upstream of the mixer. The tracer was injected into the intake pipe of the pump, ensuring that it was fully mixed with the flow delivered to the mixers. The mixer flow was adjusted using a valve downstream of the orifice meter.

The flow pumped to the mixers was measured using an ASME design orifice plate meter section calibrated at ARL's gravimetric calibration facility. This produced a flow measurement accuracy of ±2%. Without pumping, the use of the orifice meter for flow determination could artificially reduce the induced flow.

The orifice meter produced a pressure differential proportional to the square of the flow passing through it. This differential was measured manually on a manometer board, and recorded before and after each test (see Appendix B for a sample test data sheet).

4.3.2 Tracer Sampling

A continuous flow was withdrawn from each sample port using individual pumps with control valves. The majority of the flow was discharged back to the test channel (downstream of the sampling ports). The balance of the sample flow was piped through a rotameter and control valve to exit as a free jet. Twenty-five one-liter bottles were installed on a tray, and slid under the discharge jets of the sample lines to obtain simultaneous samples from all 25 points. The sample collection flows were adjusted using the rotameters so that approximately one liter of sample was collected over a period of 10 to 12 minutes at each location simultaneously. The Verification Protocol had recommended that a larger sample (two-liters) be collected over a longer sampling period (30 minutes). However, it was agreed during the development of the VTP that a shorter sampling period and smaller sample volume was adequate to obtain a representative sample given that the flow was well stabilized by the upstream flow straightener and long approach section. Further, one-liter samples provided ample volume for the required fluorometric analysis. The sample bottles were amber glass to protect light sensitive contents, with threaded green melamine caps with a chemical resistant Teflon seal. Information identifying each sample, with respect to mixer make and size, sample location, and test, was written on the bottle caps at the time of sampling (see Appendix B for a test procedure check list and test data sheet).

4.3.3 Fluorometer Calibration

A 2,500 ppb preliminary calibration solution was prepared from the stock injection solution at ARL with distilled water to expedite fluorometer calibration during testing. This was accomplished by serial dilution of the commercial 20% concentrated Rhodamine WT tracer using the dilution ratios shown in Table 4-2.

Table 4-2: Dilution Ratios for 2,500 ppb Stock Solution

From Initial Stock 20% Concentration, Serial Dilution Ratio Tracer: Distilled Water	Resulting Concentration (ppb)
1:19	1E7
1:19	5E5
1:19	2.5E4
1:9	2.5E3

At CAFRC, the 2,500 ppb concentration was further diluted using flume water to prepare the calibration samples. By this method, flume water became the primary constituent of the calibration samples, and therefore, any effects related to the water quality were common to the calibration and test samples. Calibration samples were prepared by sequential dilution using the dilution ratios shown in Table 4-3.

Table 4-3: Dilution Ratios for Calibration Samples

From Initial 2,500 ppb Solution Serial Dilution Ratio Tracer: Flume Water	Resulting Calibration Concentrations (ppb)
1:9	250 (used only to produce the 12.5ppb sample)
1:49 using 2,500 ppb	50
1:99 using 2,500 ppb	25
1:19 using 250 ppb	12.5
0:1 Flume Water	0

The 1:9 dilution with flume water was used to produce the 12.5 ppb concentration. The 50 ppb and 25 ppb solutions were prepared directly from the 2,500 stock solution. All calibration solutions were mixed in the field so that the flume water was the major constituent (always > 98%) in each calibration sample. This ensured that both the calibration samples and the test samples were subjected equally to any effects due to flume water quality.

The 2,500 ppb solutions were used to prepare four calibration solutions of 0, 12.5, 25, and 50 ppb for fluorometer calibration (all concentrations are relative to the injected stock solution of 2×10^7 ppb). The fluorometer was calibrated with the above samples and recorded on individual calibration data sheets (provided in Appendix B).

From each calibration, a linear equation was generated that was used to convert the recorded fluorometer output (volts (V_o)) to a tracer concentration for each sample collected at:

$$\text{Concentration} = (m \times V_o) + b \tag{4-1}$$

where

m = slope of the linear equation
b = intercept of the linear equation
V_o = voltage (fluorometer output)

Equation 4-1 was used to determine the tracer concentration of all samples based on the recorded fluorometer voltage output.

Based on experience, the calibrations of this type, using field water, can be expected to produce a linear response in fluorometer output that was within ±2% full scale, or about 2 to 3 ppb. Deviation above this limit would be suspect, and a second set of calibration samples would be prepared using the prepared stock (2,500 ppb) and flume water (enough flume water was withdrawn to prepare multiple calibration samples). All calibration data proved to be within the ±0.5% full-scale limit.

The fluorometer was calibrated in this way for each mixer at each flume velocity. Each calibration was evaluated in the field in terms of the correlation between the serial dilution samples and the best-fit calibration equation (Equation 4-1). All calibration samples proved to be within ±0.5% of the best-fit line, based on the usual full-scale value (100 ppb) of the fluorometer scale being used. For repeat analysis tests, the corresponding calibration samples were used to re-calibrate the fluorometer. Typical calibration results (linear curve fit and error plots) are included in Figure 4-2.

4.3.4 Tracer Concentration

A portable computer with a 12-bit analog-to-digital converter recorded fluorometer voltage output and the output from the two RTD thermometers, which measured the sample water and instrument (light source filter) temperatures. A platinum resistance temperature sensor, mounted in an 1/8-inch diameter rod, was used to measure each water sample temperature, so as to correct measured fluorometer voltage output to calibration water temperature (Equation 3-2). Fluorometer output, water temperature, and filter temperature were read at eight hertz and, after 80 readings (about 10 seconds), the averages and standard deviations were calculated, stored, and printed. During data acquisition, individual temperature and fluorometer readings were displayed on the PC monitor for manual recording on data sheets. Variation of the corrected output from the previous test point was displayed as a percent to show trends on a magnified scale. After the fluorometer output reached a steady value for each sample (approximately 20 seconds), three 10-second readings were averaged and recorded on a test data sheet (see Appendix B). The linear fluorometer calibration equation established for each mixer test and flume velocity was used to convert the voltage output to tracer concentrations (in ppb) for each of the corresponding samples.

The concentration of each sample collected during tests was determined once at CAFRC and two sets of the mixer samples were chosen at random and re-analyzed while at CAFRC. The results of the repeat analyses (RA Tests) are discussed in Section 6.3.

4.4 Test Flume Velocity Distribution

The velocity profile upstream of the mixer location in the test flume was mapped by measuring the velocities at 49 discrete points using an acoustic Doppler velocity meter. A flow conditioner located at the upstream end of the flume was adjusted by changing porosity until the distribution profile was within ±10% of the overall average. The measured velocity distribution was uniform with measured velocities within ±4% of the average at the low flume velocity and within ±8% of the average at the higher velocities. Figure 4-3 illustrates the velocity distribution within the test flume for the three test velocities of 0.5 ft/sec, 1.25 ft/sec, and 3.0 ft/sec.

Each point velocity measurement was recorded over a period of two minutes at a sampling frequency of 10 hertz and included all the three components of the velocity at each location. The RMS values of fluctuations of each component of the velocity from its mean were used to characterize the flume turbulence intensity. Using this method, the turbulence intensity was, on the average, 12% of the average flume velocity. The root mean squared (RMS) turbulence intensities for each velocity are identified to the right of each plot in Figure 4-3.

4.5 Test Flume Flow Calibration

The average of the 49 velocity measurements recorded for each desired flume test velocity (or flow) was used as the *actual* flume velocity. Using the flow calculated from the actual flume velocity and the flume test section area, a weir discharge coefficient at each of the three weir positions required to achieve the test flows was calculated using the following equation:

$$Q = (C \times L \times H)^{3/2} \tag{4-2}$$

where

Q	=	the flow in ft^3/sec,
L	=	the weir length (10 ft),
H	=	the depth of water over the weir in ft, and
C	=	the weir discharge coefficient (specific to each weir position)

The discharge coefficient C varied, as listed below for the three flows (velocities):

Average Flume Velocity (ft/sec)	C
0.547	4.78
1.24	4.10
3.06	4.16

These *position-sensitive* weir coefficients were used to calculate the flows (and therefore, flume velocities) using the recorded values of water level and weir position during each test.

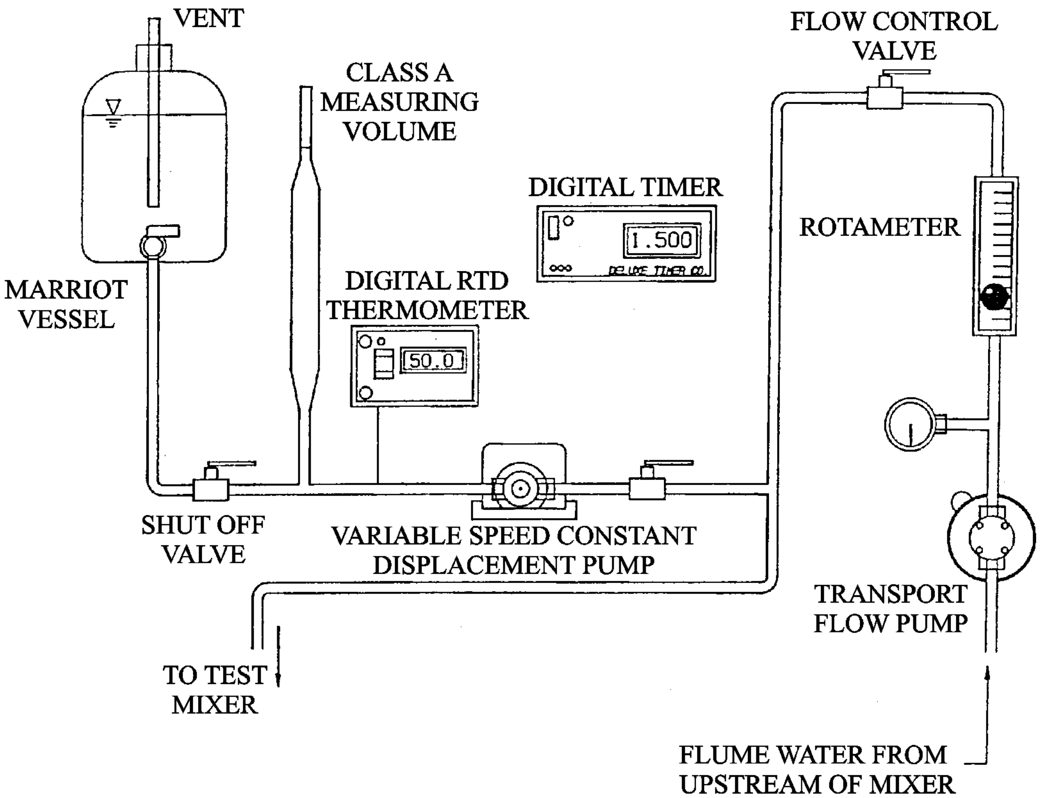


Figure 4-1: Schematic of Dye Injection System

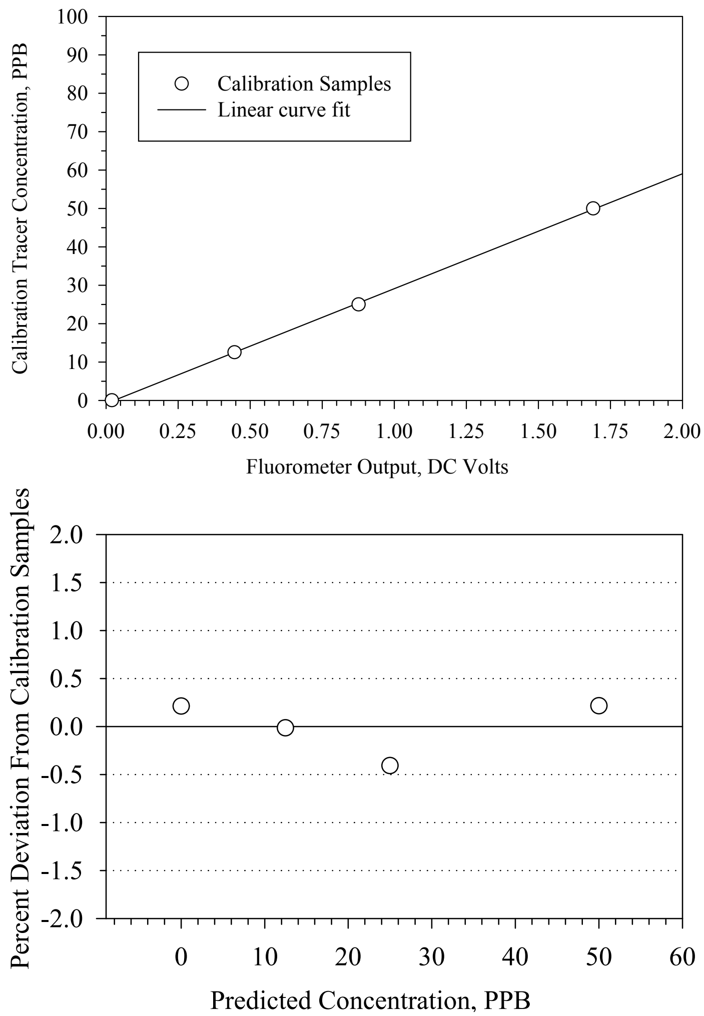


Figure 4-2: Typical Calibration Data

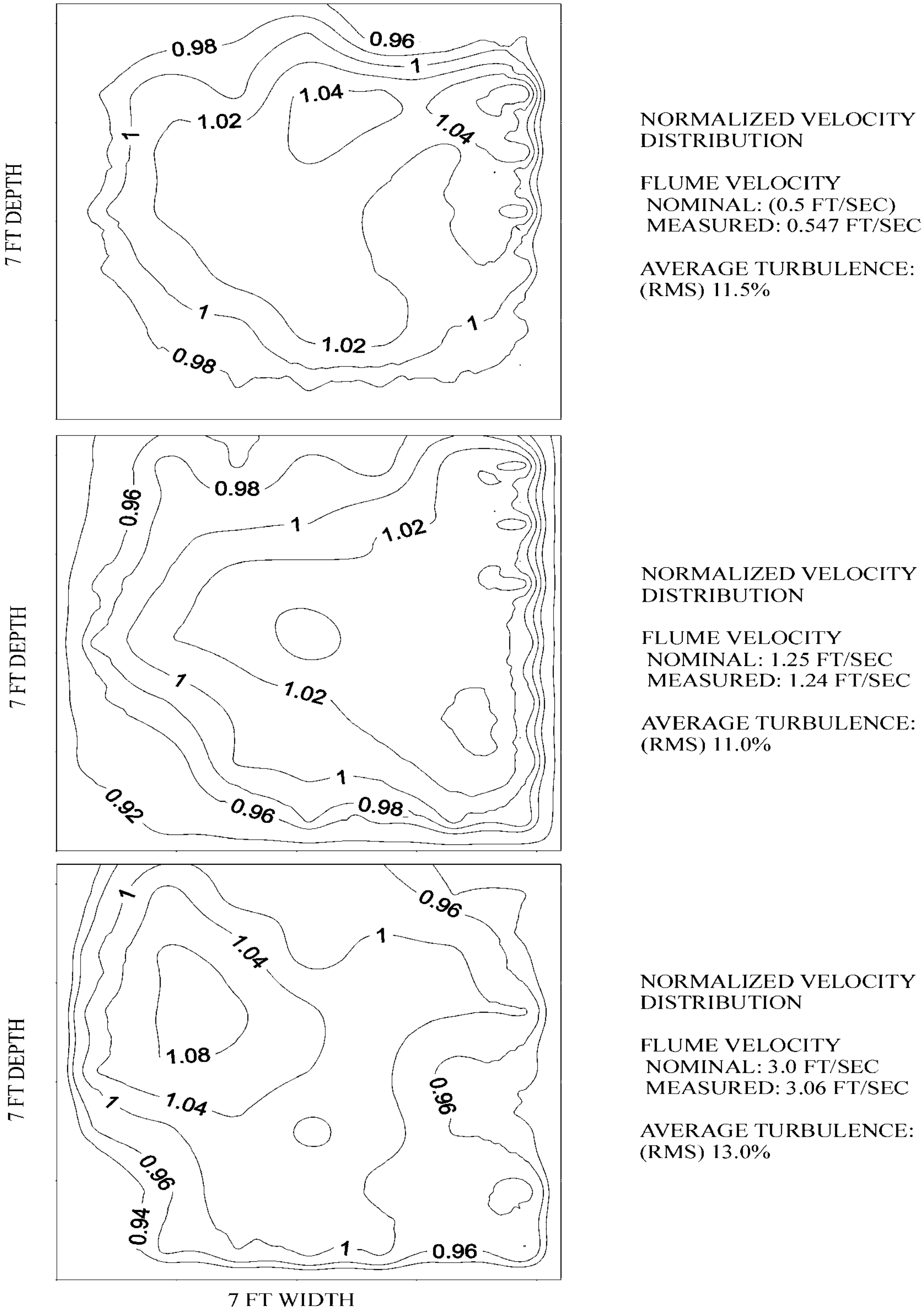


Figure 4-3: Flume Velocity Distributions

5 Results and Discussion

5.1 Tracer Concentration Distributions

The tracer concentration (in ppb) was determined for each of the 25 samples collected per test as described in section 4.3. This data is tabulated in Appendix D. To facilitate interpretation, tracer concentration values were normalized by dividing the value of each sample by the theoretical uniform mixed concentration (C_u) for test condition under which the samples were collected. The theoretical uniform mixed concentration is calculated using Equation 5-1 (derived from Equation 3-1), as follows:

$$C_u = (C_i \times Q_i) \; / \; Q_t \qquad (5\text{-}1)$$

Where

C_i = injected tracer concentration
Q_i = injected tracer flow
Q_t = total flow in flume

The total flume flow (Q_t) and average tracer injection flow (Q_i) were calculated as the averages of the flows measured just prior to and immediately following each test. The injected tracer concentration, C_i, was constant for all tests (2×10^7 ppb).

The average tracer concentration for each sampling port, as described in Section 4.3.3, was normalized by dividing the sample concentration by the theoretical uniform concentration C_u, which is defined as:

C_u = tracer stock concentration × tracer feed flow rate / flume water flow rate

A normalized concentration of one represents perfect mixing. The normalized concentrations at the 25 sampling ports for each of the three cross-sections were used to generate an isopleth diagram for each flow condition and sampling location.

For some test conditions, the peak tracer concentrations were above the range used to calibrate the fluorometer. In order to calculate the higher concentration samples, the fluorometer sensitivity setting was adjusted from X31.6 to X10.0. The sensitivity setting, as described in Section 3.4.3, changes the output of the fluorometer to allow reading of the higher concentrations.

The normalized values for each test were plotted at their respective locations and lines of equal concentration (isopleths) were drawn by interpolation to define the mixer plume.

In general, as might be expected, the mixers produced a roughly circular plume with higher concentrations in the center. Figure 5-1 illustrates such a distribution produced five feet downstream of the 5 HP mixer operating in a nominal flume velocity of 1.25 ft/sec (actual velocity 1.23 ft/sec).

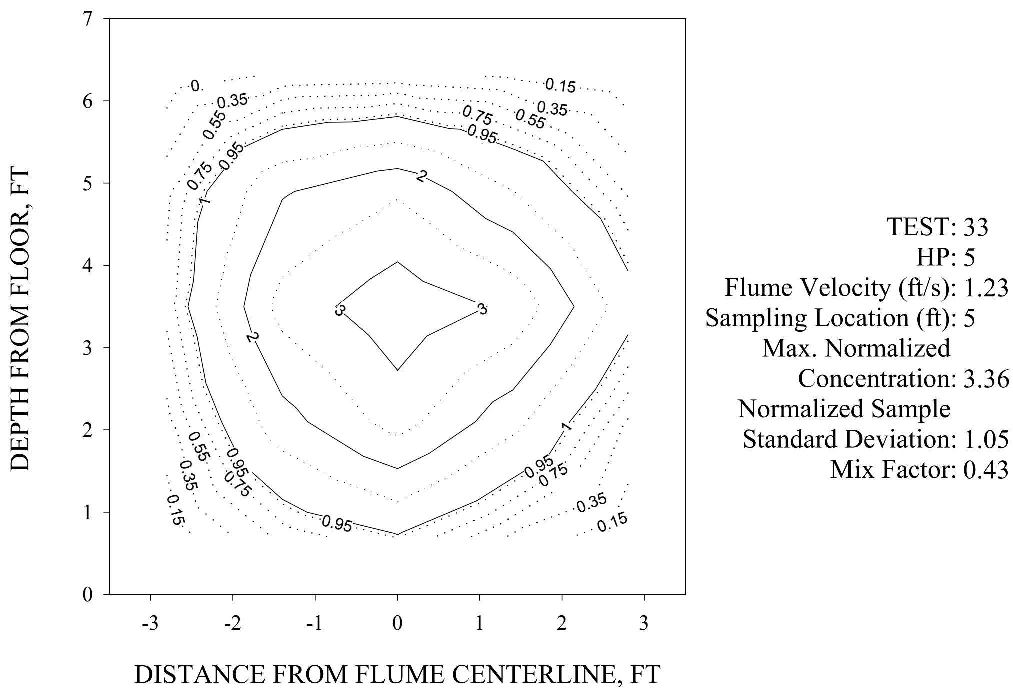


Figure 5-1: Typical Mixer Plume at Medium Flume Velocity

In general, smaller plume areas and higher peak concentrations were observed under the higher flow velocity conditions. In other words, as the energy imparted by the mixer became smaller in relation to the kinetic energy of the flow in the flume (related to flow velocity), the level of mixing observed also lessened. The plume in Figure 5-2 is from the same 5 HP mixer operating at the higher flume velocity of 3.0 ft/sec. It can be seen that the maximum (peak) normalized concentration increased from approximately 3 at the 1.25 ft/sec velocity (Figure 5-1) to almost 11 at the 3 ft/sec velocity (Figure 5-2).

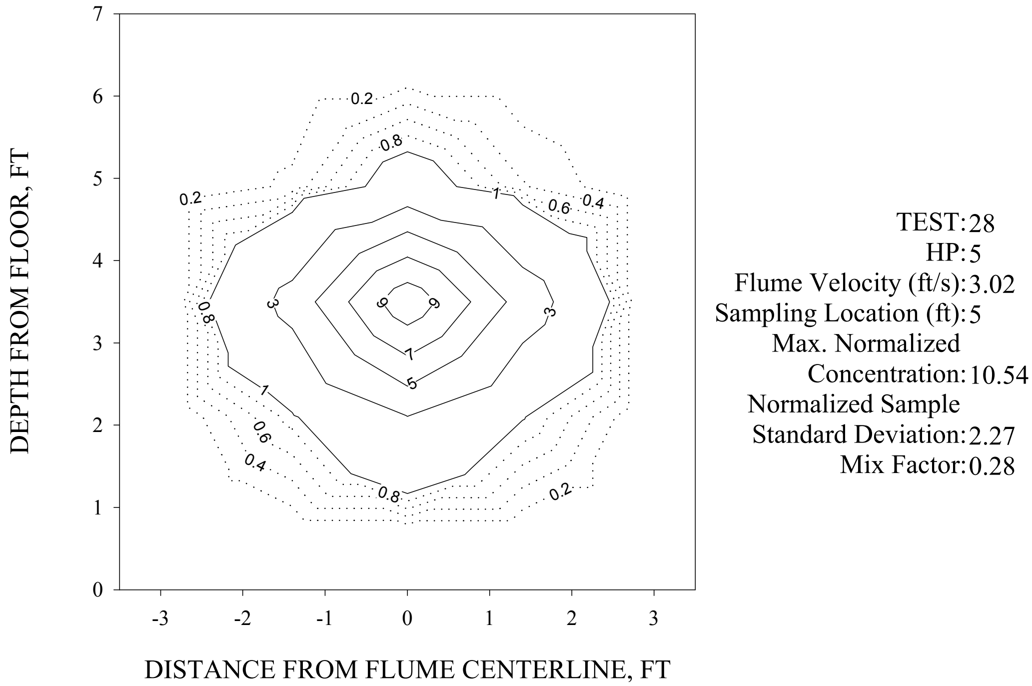


Figure 5-2: Typical Mixer Plume at High Flume Velocity

At the lowest flume velocity (0.5 ft/sec), the tracer concentrations are more evenly distributed across the flume cross-section and may approach uniform mixing as the plume was able to spread rapidly. An example of this is shown in Figure 5-3, where it can be seen that the mixer was able to propel the tracer in a fairly uniform manner throughout the flume cross-section. In this case, the normalized concentrations near the center of the flume are about 25% above the theoretical uniform concentration, while the lowest normalized concentrations (in the corners of the flume) are about 50% of the theoretical uniform concentration.

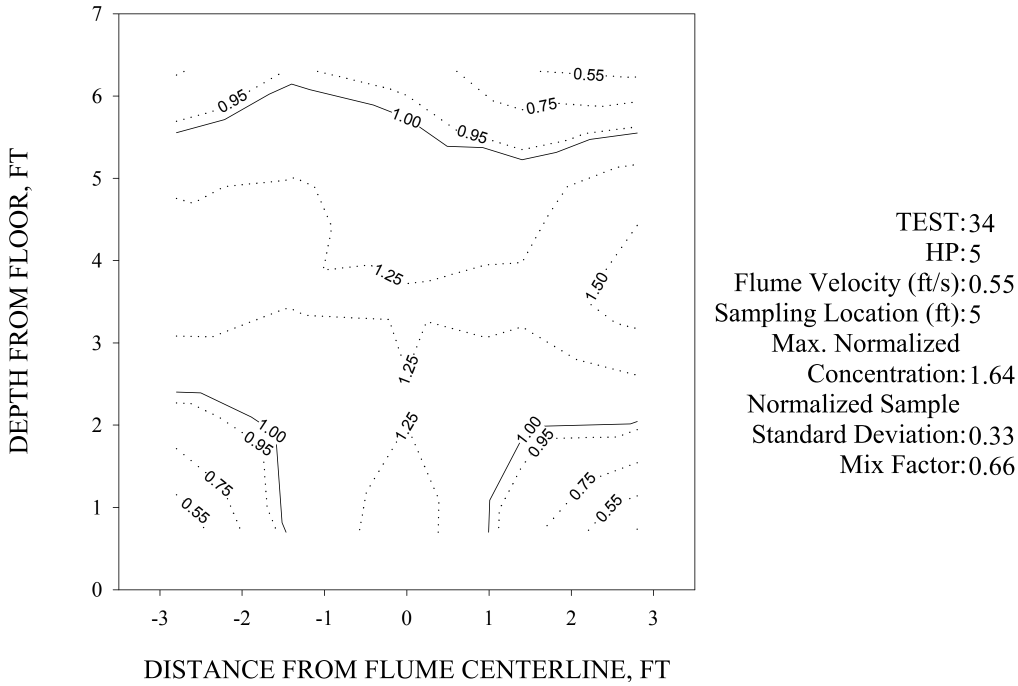


Figure 5-3: Typical Mixer Plume at Low Flume Velocity

The complete set of concentration distribution plots is shown in Figures 5-4 through 5-12. Each figure shows the data plots from a single mixer at a single velocity and includes a plot for each of the three downstream distances (5, 10, and 20 ft) from the mixer. The plots for Test Series A (5 HP) are found in Figures 5-4 through 5-6. The plots for Test Series B (10 HP) and Test Series C (20 HP) are found in are found in Figures 5-7 through 5-9 and Figures 5-10 through 5-12, respectively. Although these plots of the mixer plumes provide a visual means to evaluate the performance of the mixer, the following sections attempt to quantify mixer performance in terms of the area of the mixer plume, the maximum (peak) concentration, and the variation in concentration within the mixer plume.

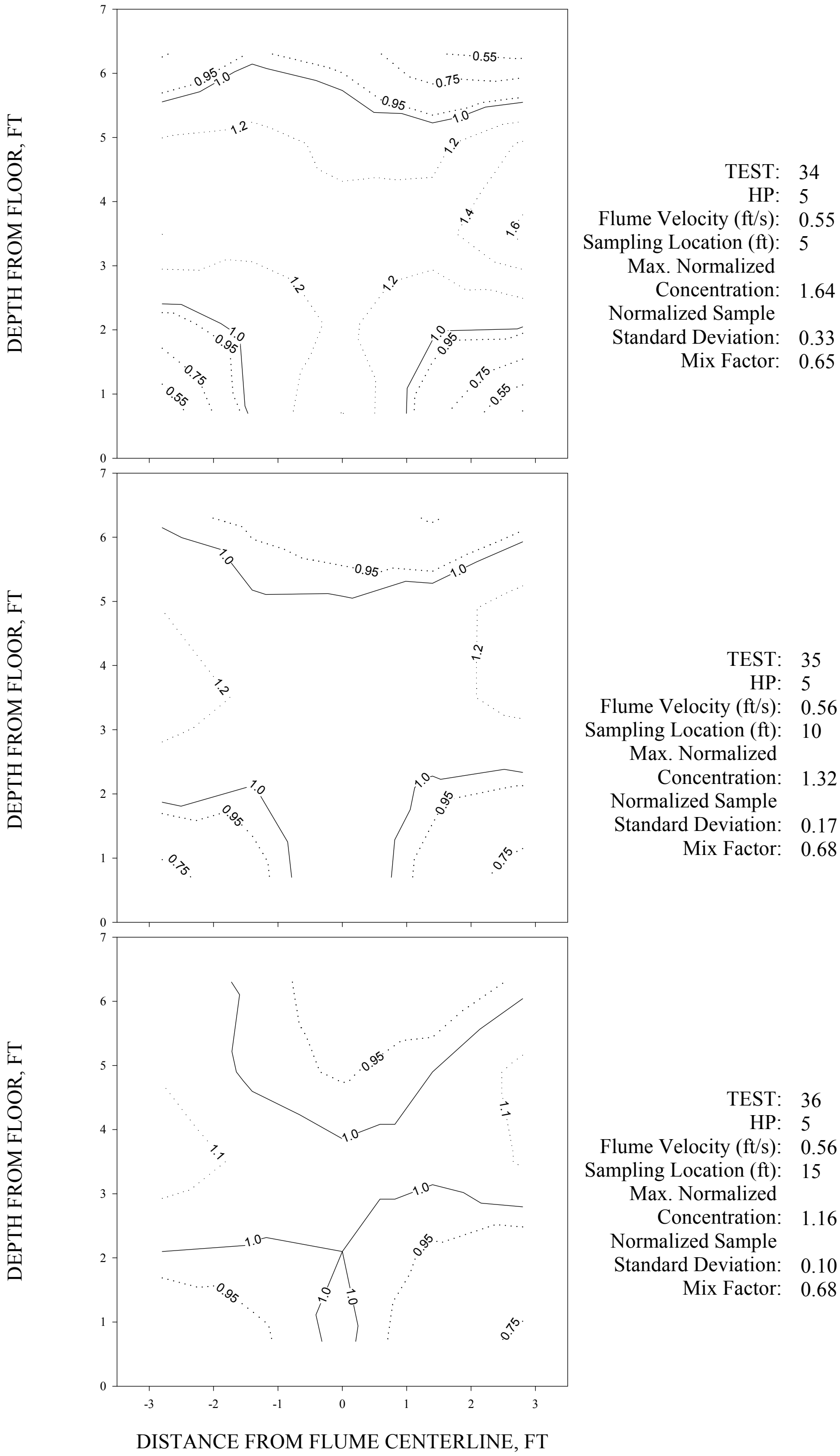


Figure 5-4: Non-Dimensional Concentration Distribution For The 5 HP Mixer At 0.5 ft/sec Flume Velocity

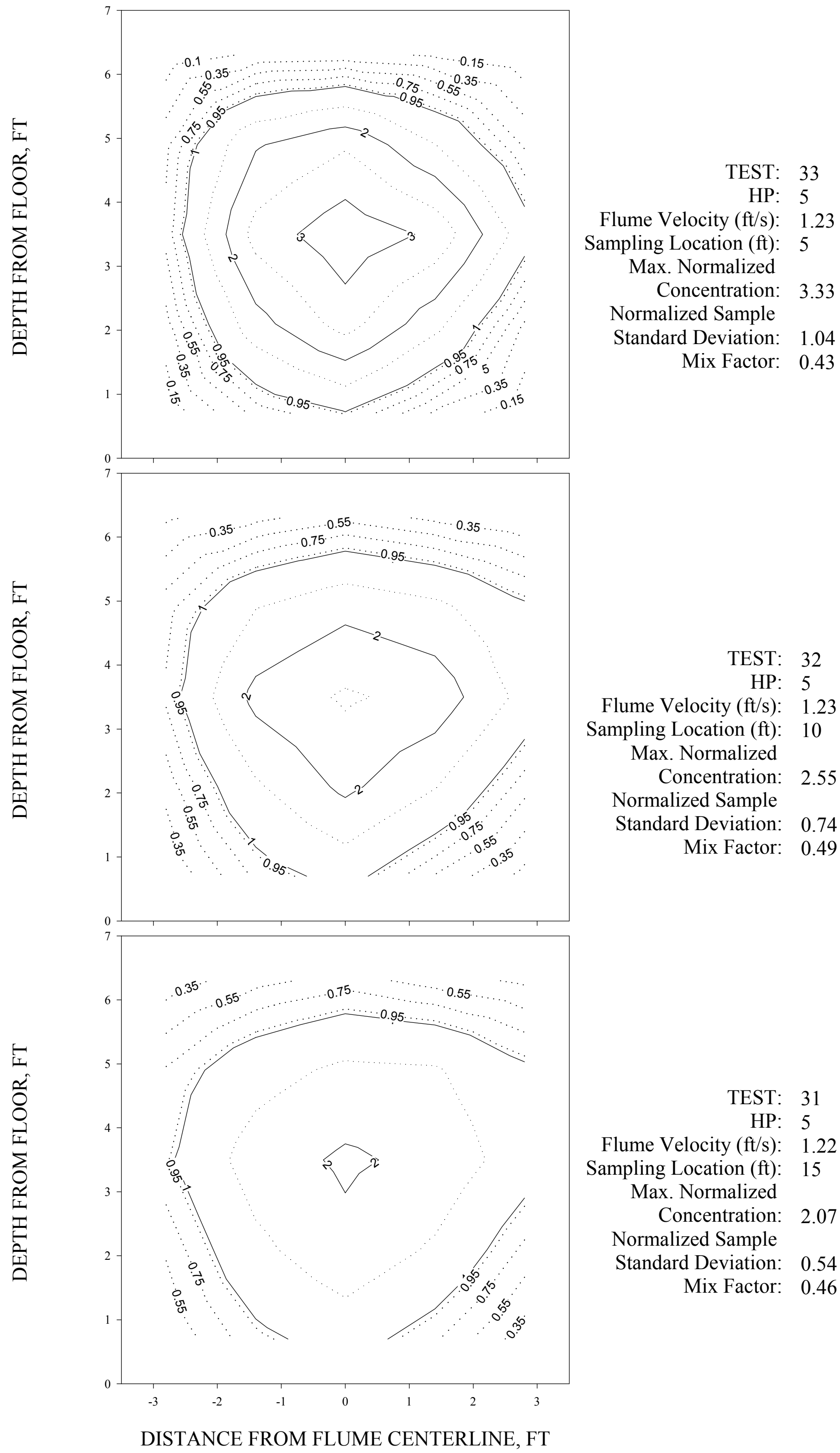
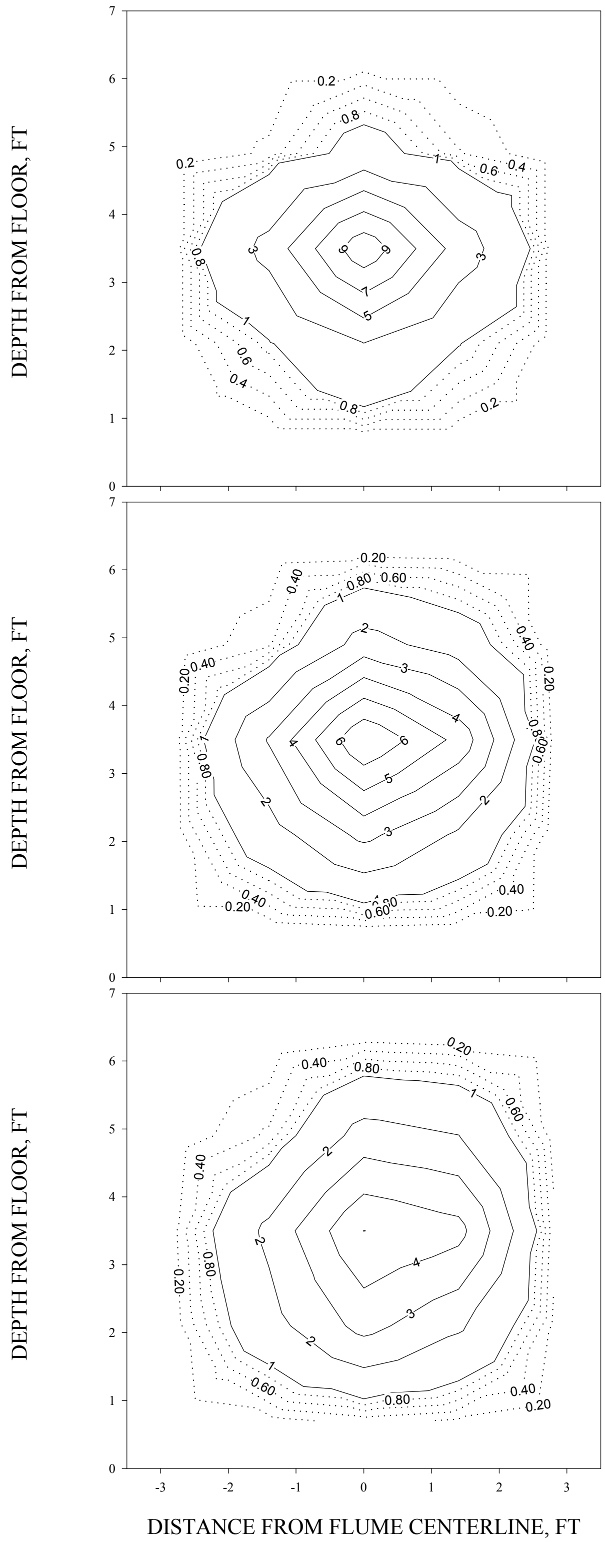


Figure 5-5: Non-Dimensional Concentration Distribution For The 5 HP Mixer At 1.25 ft/sec Flume Velocity



TEST: 28
HP: 5
Flume Velocity (ft/s): 3.08
Sampling Location (ft): 5
Max. Normalized Concentration: 10.75
Normalized Sample Standard Deviation: 2.31
Mix Factor: 0.28

TEST: 29
HP: 5
Flume Velocity (ft/s): 3.08
Sampling Location (ft): 10
Max. Normalized Concentration: 7.14
Normalized Sample Standard Deviation: 1.80
Mix Factor: 0.35

TEST: 30
HP: 5
Flume Velocity (ft/s): 3.07
Sampling Location (ft): 15
Max. Normalized Concentration: 5.11
Normalized Sample Standard Deviation: 1.48
Mix Factor: 0.36

Figure 5-6: Non-Dimensional Concentration Distribution For The 5 HP Mixer At 3.0 ft/sec Flume Velocity

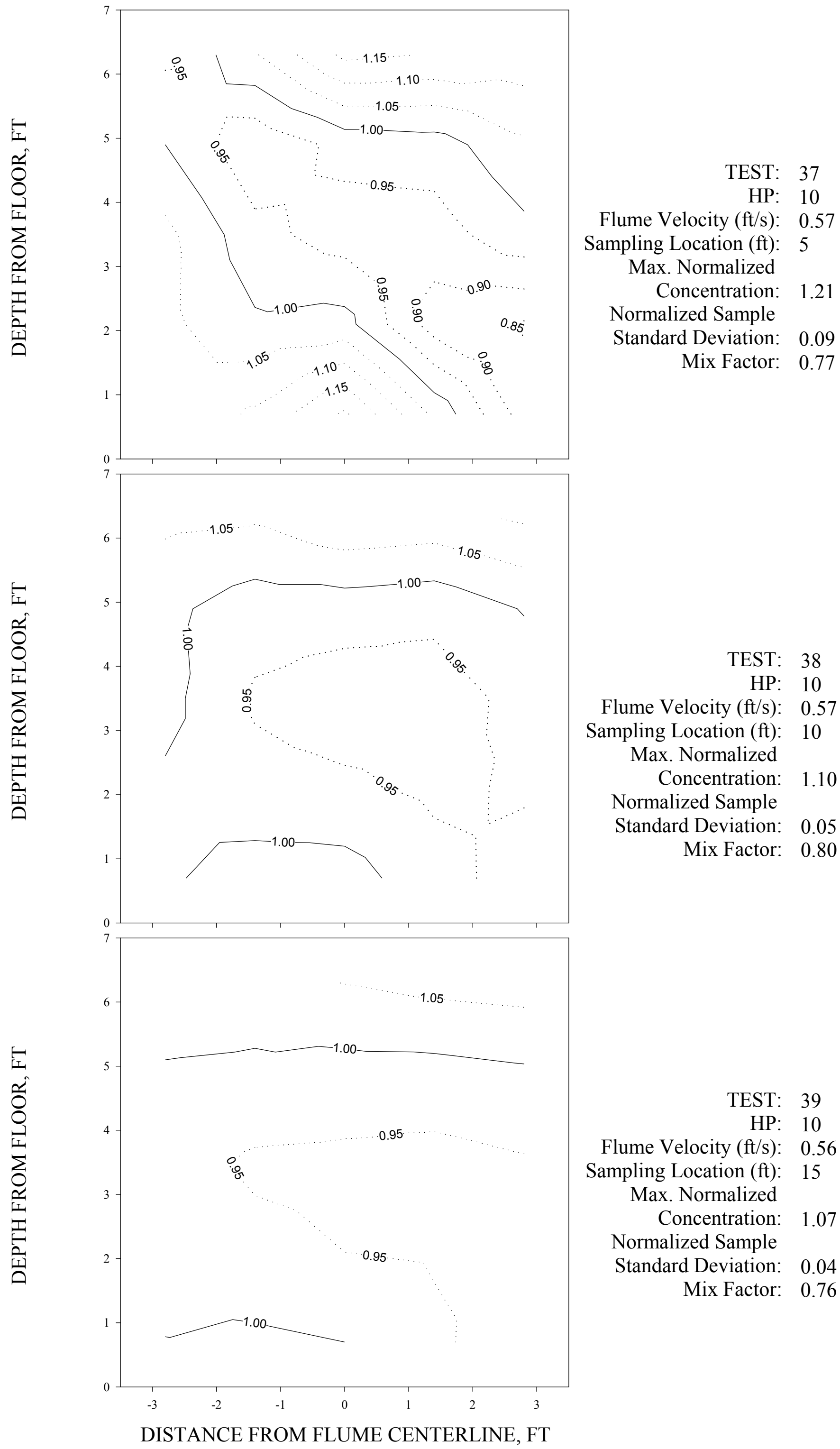


Figure 5-7: Non-Dimensional Concentration Distribution For The 10 HP Mixer At 0.5 ft/sec Flume Velocity

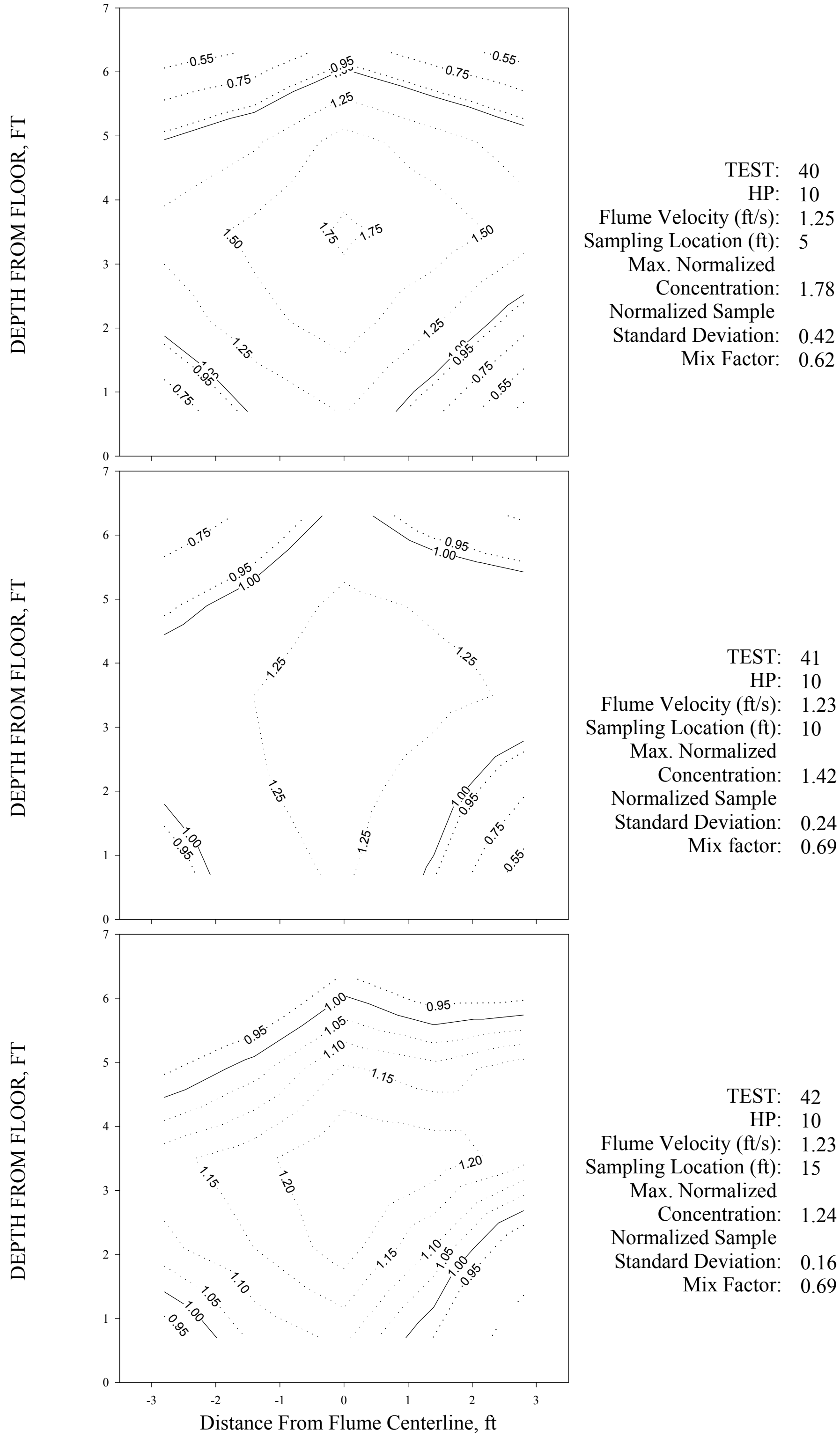


Figure 5-8: Non-Dimensional Concentration Distribution For The 10 HP Mixer At 1.25 ft/sec Flume Velocity

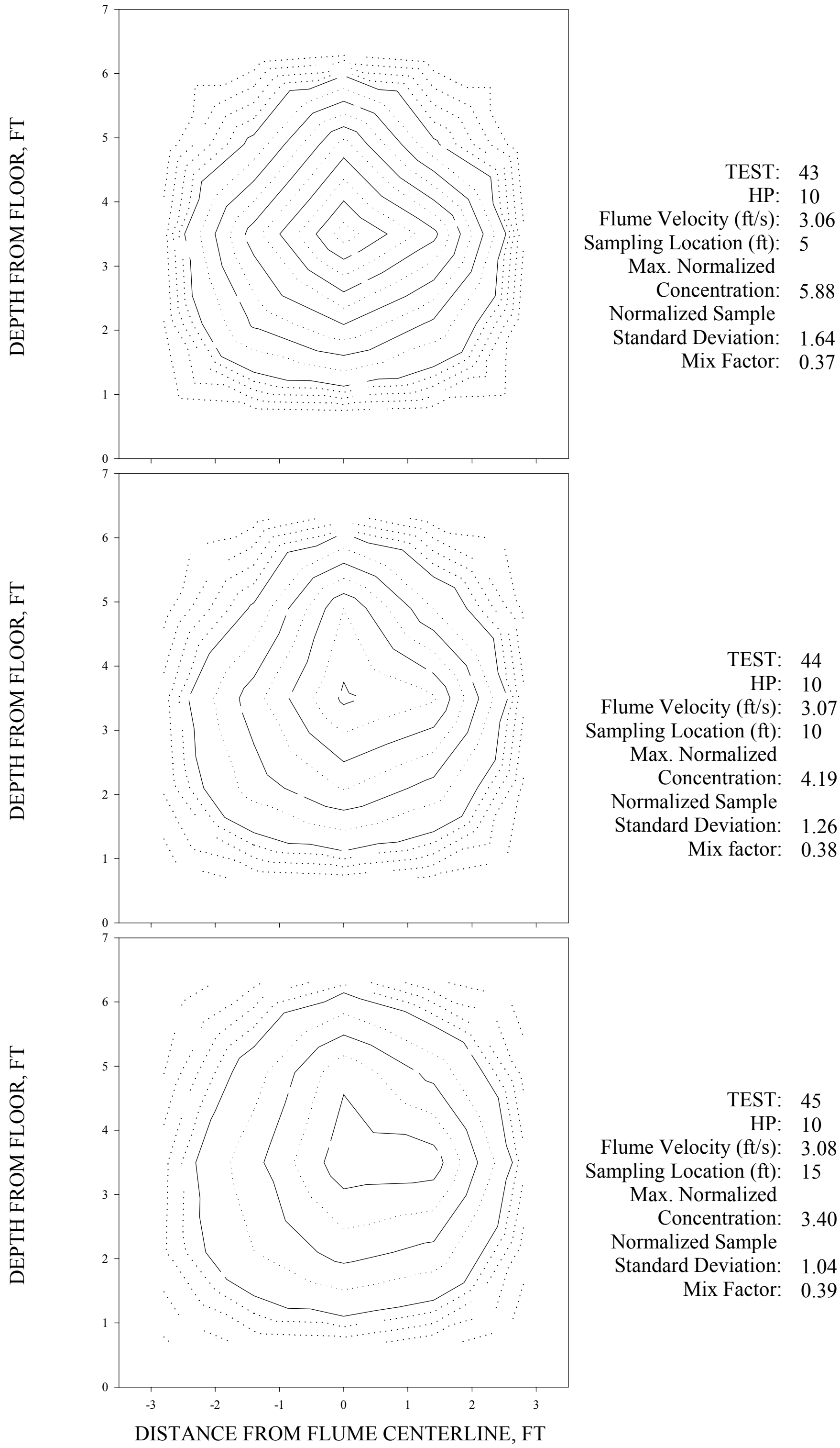


Figure 5-9: Non-Dimensional Concentration Distribution For The 10 HP Mixer At 3.0 ft/sec Flume Velocity

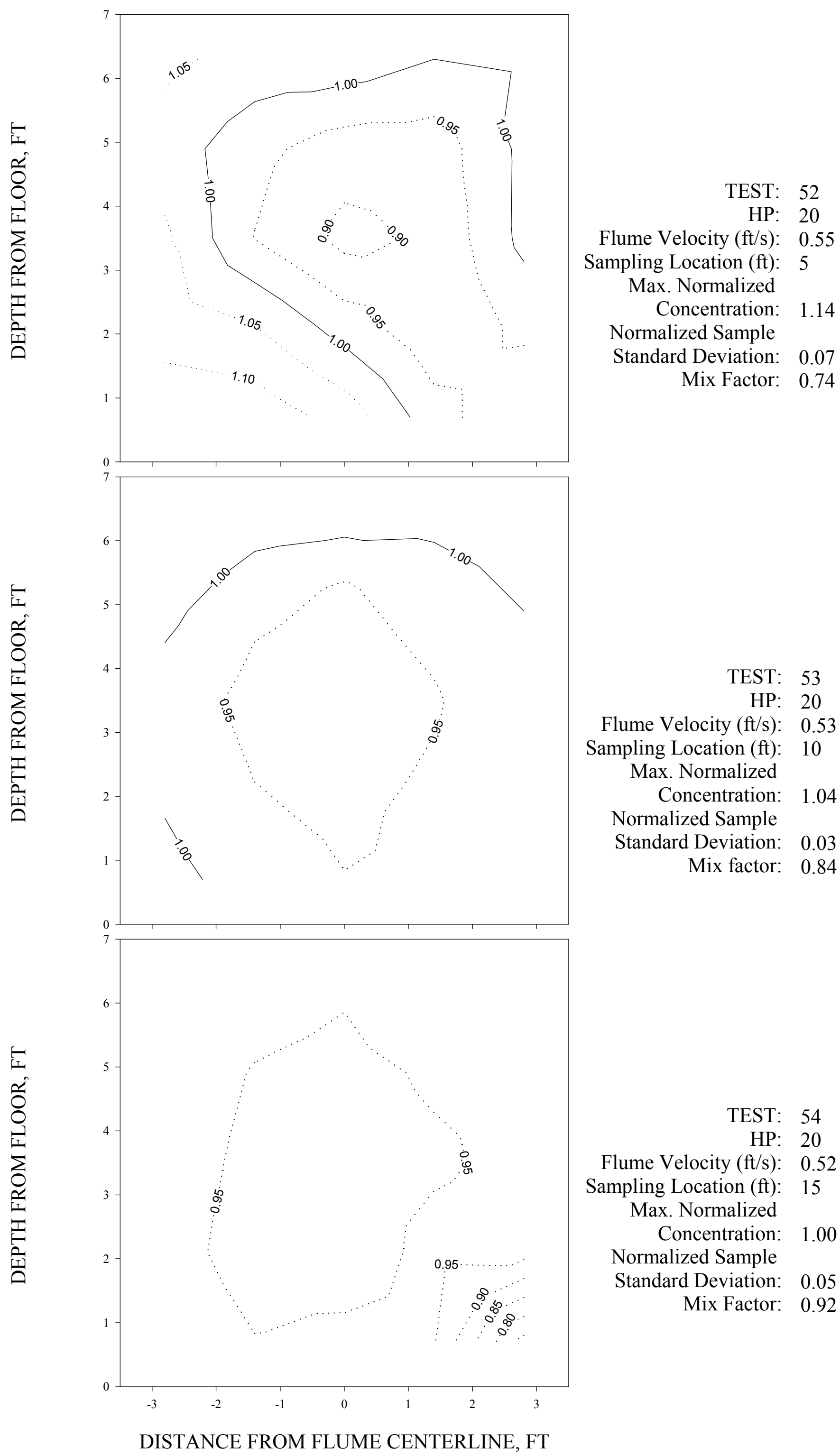


Figure 5-10: Non-Dimensional Concentration Distribution For The 20 HP Mixer At 0.5 ft/sec Flume Velocity

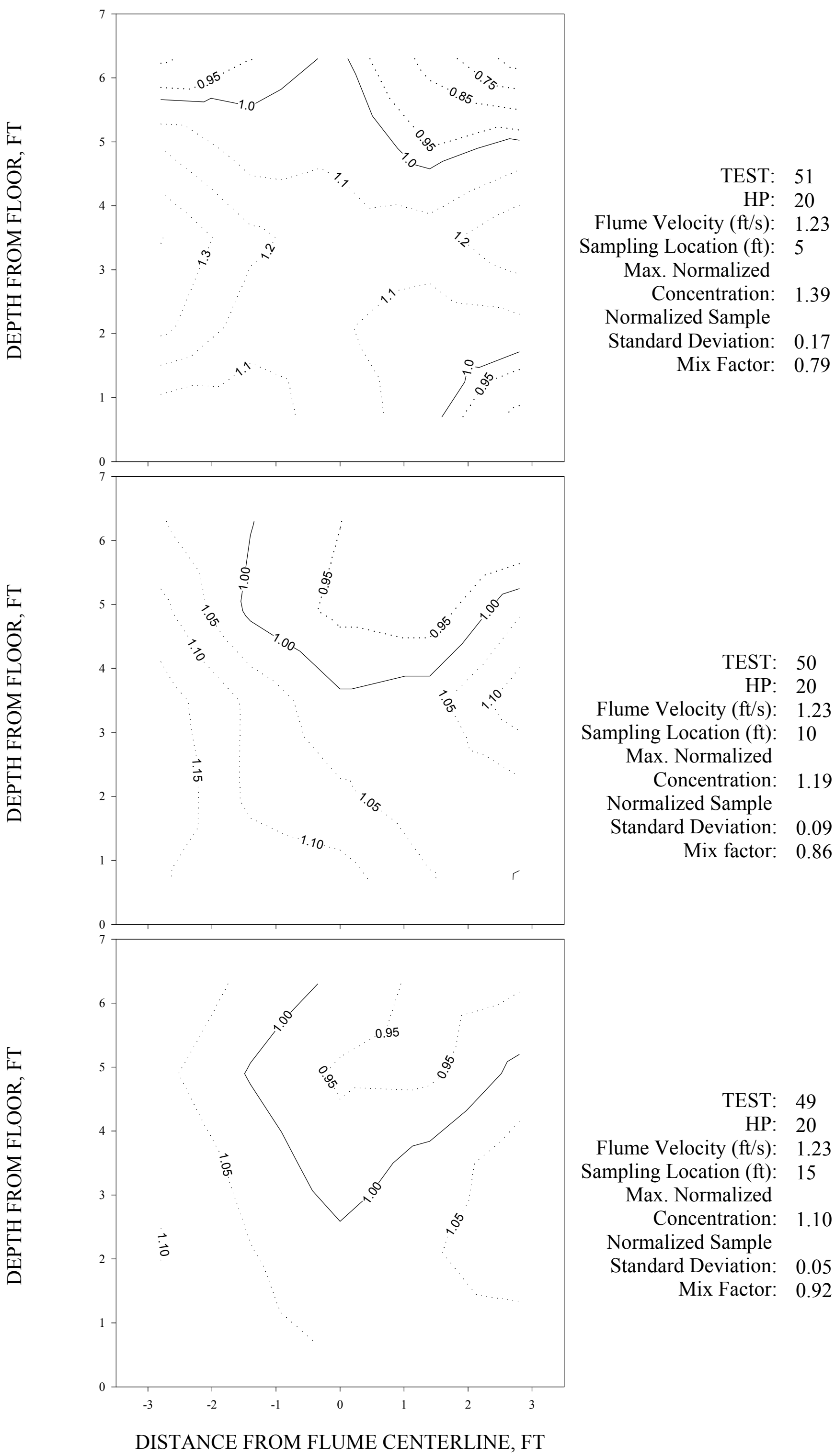


Figure 5-11: Non-Dimensional Concentration Distribution For The 20 HP Mixer At 1.25 ft/sec Flume Velocity

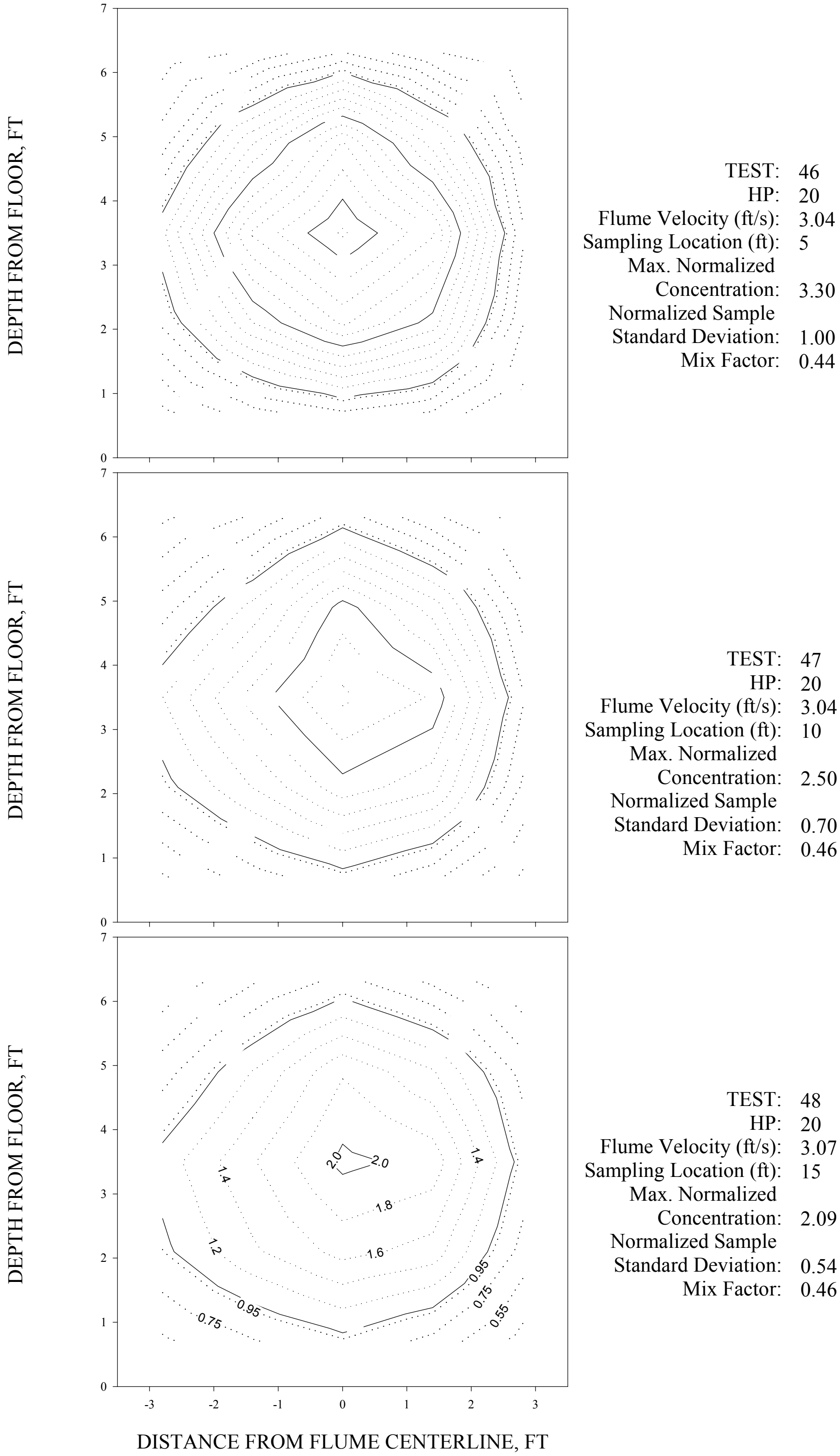


Figure 5-12: Non-Dimensional Concentration Distribution For The 20 HP Mixer At 3.0 ft/sec Flume Velocity

5.2 Mix Factor

For each test, a Mix Factor was calculated using the corresponding tracer concentration distribution plot (isopleth diagram). A Mix Factor of 1 represents the concentration if the tracer was equally dispersed throughout the cross-section of the flume. The Mix Factor is defined as,

$$\text{Mix Factor} = A_{.95} / A_T \tag{5-2}$$

where

$A_{.95}$ = channel cross-sectional area where tracer concentration >(.95 × C_u)

A_T = total channel cross sectional area

The Mix Factor indicates the area of the channel that experienced complete mixing. In the above definition, the 95% value instead of the 100% value was used to allow for likely inaccuracies of flow and concentration measurements.

The concentration distribution plots were used to calculate the Mix Factor for each set of plume data. The Mix Factor for each test is reported in the margin of the corresponding concentration distribution plot (Figures 5-4 through 5-12). The Mix Factor provides insight into the area (relative to the test flume cross-section) affected by a concentration of chemical greater than the theoretical uniform concentration.

Due to the complex and varying shape of the 0.95 isopleths, no reliable automated method was available to measure its area. Instead, the areas bounded by the 0.95 isopleths or higher were measured manually using a planimeter on a hard copy of each plot. The planimeter was also used to measure the area of the flume cross-section on each plot (roughly 3" x 3" in the plots) so as to verify and correct the planimeter predicted areas. The former was divided by the latter to produce the Mix Factor. For cases where the 0.95 isopleth extended to the limits of the sampling rig and did not form a closed boundary, the lines were extended, following their ending slope, until they intersected the flume wall or each other.

5.2.1 Affect of Downstream Distance on Mix Factor

The Mix Factor for perfectly uniform mixing would be a value of 1.0. It is evident from a plot of Mix Factor versus distance downstream from the mixer that the extent of mixing is enhanced with distance. An example of such a plot is shown in Figure 5-13 for the tested 5 HP mixer. Figure 5-13 shows the Mix Factor increasing with distance from the mixer; meaning that the area within the 0.95 isopleth was increasing as the plume moved away from the mixer. Presumably, the Mix Factor may asymptotically approach the value of 1.0 at some large distance downstream of the mixer.

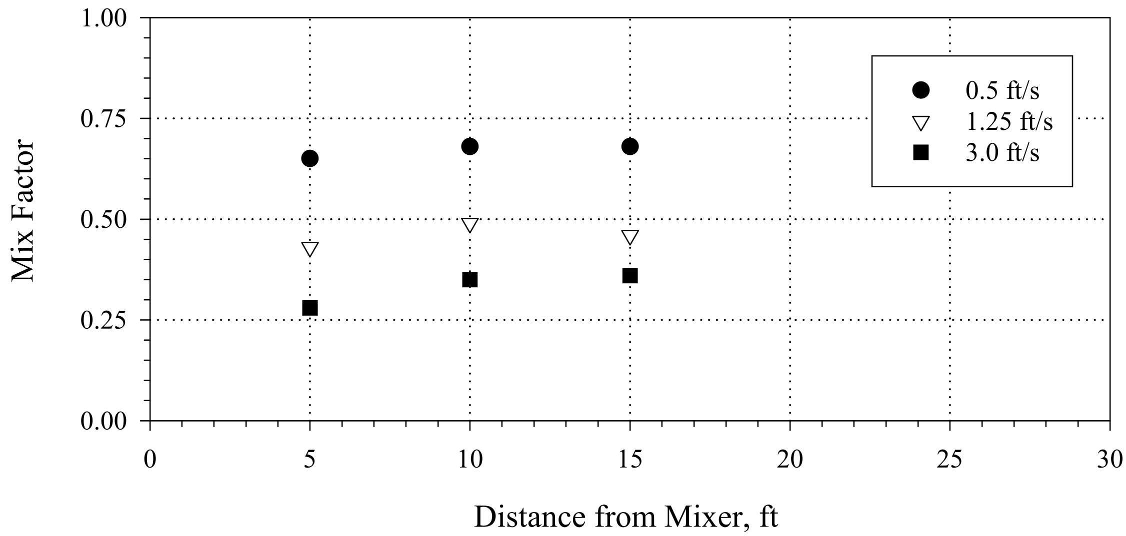


Figure 5-13: Example of Mix Factor Versus Distance From Mixer—5 HP Mixer

5.3 Maximum (Peak) Normalized Concentration

The Maximum (Peak) Normalized Concentrations are reported for each test as an indicator of the uniformity of the plume concentrations produced by the mixer. The maximum normalized concentration for each test is reported in the margin of the corresponding concentration distribution plot (Figures 5-4 through 5-12).

It is possible to have two sets of plume data with similar Mix Factors but with substantially different maximum (peak) concentrations. Figure 5-14 shows the results of concentration measurements for the 5 HP mixer at the 3.0 ft/sec flume velocity at the 10 ft and 15 ft downstream sampling location. At both the 10-ft and 15 ft downstream sampling locations, the calculated Mix Factor is approximately equal, at 0.35. With no further information, this could lead to an erroneous conclusion that the plume does not spread as it moves downstream away from the mixer. The maximum (peak) normalized concentrations from the two sets of data however reveal that the plume is in fact continuing to disperse as it moves downstream, with the maximum (peak) value decreasing from seven to five times the theoretical average as it moves from ten feet downstream to fifteen feet downstream.

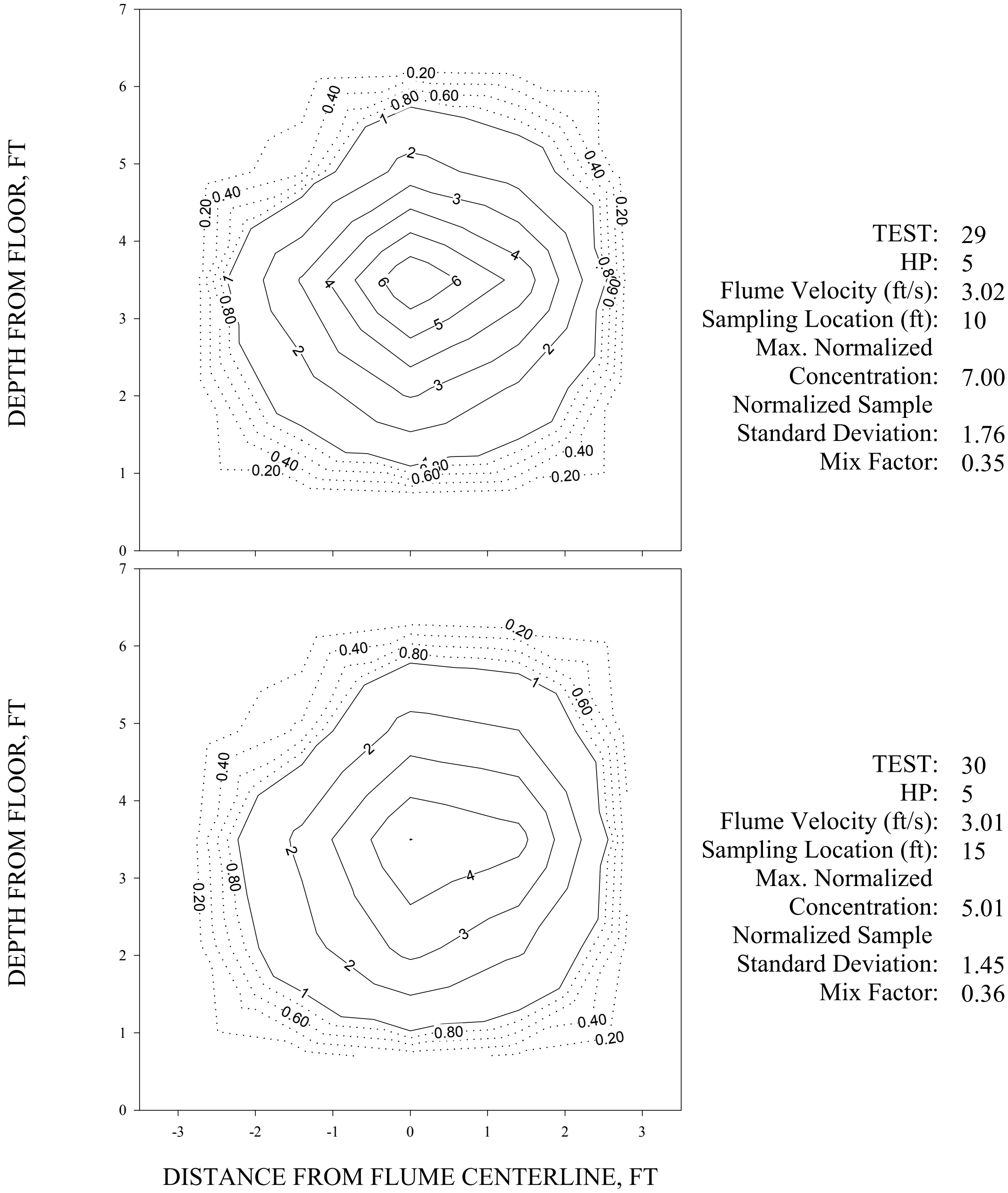


Figure 5-14: Example of Similar Mix Factors With Differing Maximum (Peak) Concentrations

5.3.1 Affect of Downstream Distance on Maximum (Peak) Normalized Concentration

The Maximum (Peak) Normalized Concentration versus distance downstream of the mixer can be plotted as shown in Figure 5-15. As with the Mix Factor, perfect mixing would be indicated by a maximum normalized concentration value of 1.0. The maximum (peak) normalized values quickly decreased with distance, by approximately 50% between the 5 ft and 15 ft sample location. This indicates that the mixer is imparting significant turbulence that continues to mix and distribute the chemical within the plume as it travels downstream. However, as the Mix Factors were much less than 1.0, the effective mixing (disinfectant dispersion) was maintained within a limited area of the flume cross-section and the area occupied by the plume itself did not increase rapidly with increasing distance downstream.

5.4 Uniformity of Tracer Distribution of Tracer (Standard Deviation)

As described above, the mixing zone can be represented by the area bounded by concentrations above the theoretical uniform concentration, and the overall range of concentration can be expressed by the highest and lowest measured concentrations. The uniformity of the distribution of tracer concentrations across the flume flow cross-section, i.e., the variation around the average concentration, can be expressed mathematically as the standard deviation of the (25 point) sample data sets. The concentration standard deviation for each test is reported in the margin of the corresponding concentration distribution plot (Figures 5-4 through 5-12). More uniform mixing is represented by smaller standard deviations. A Standard Deviation of 0.0 would represent complete uniformity of mixing.

5.4.1 Affect of Downstream Distance on Uniformity of Concentration

The standard deviation of concentrations within the flume cross-section is directly related to the variations of the concentration values. Therefore, when the standard deviations of the normalized concentrations versus distance from the mixer are plotted, as shown in the example Figure 5-16, the extent and uniformity of mixing is realized, as good mixing would be indicated by a low standard deviation.

5.5 Mixer Power

The power used by each mixer was recorded for each test. The average values of voltage and amperage were calculated from readings taken just before and after the samples were collected (see Appendix E for raw data). Mixer power was calculated using equation 5-3:

$$\text{Power (Watts)} = \text{Amps} \times \text{Volts} \tag{5-3}$$

The power calculations for each mixer are summarized in Tables 5-1, 5-2, and 5-3.

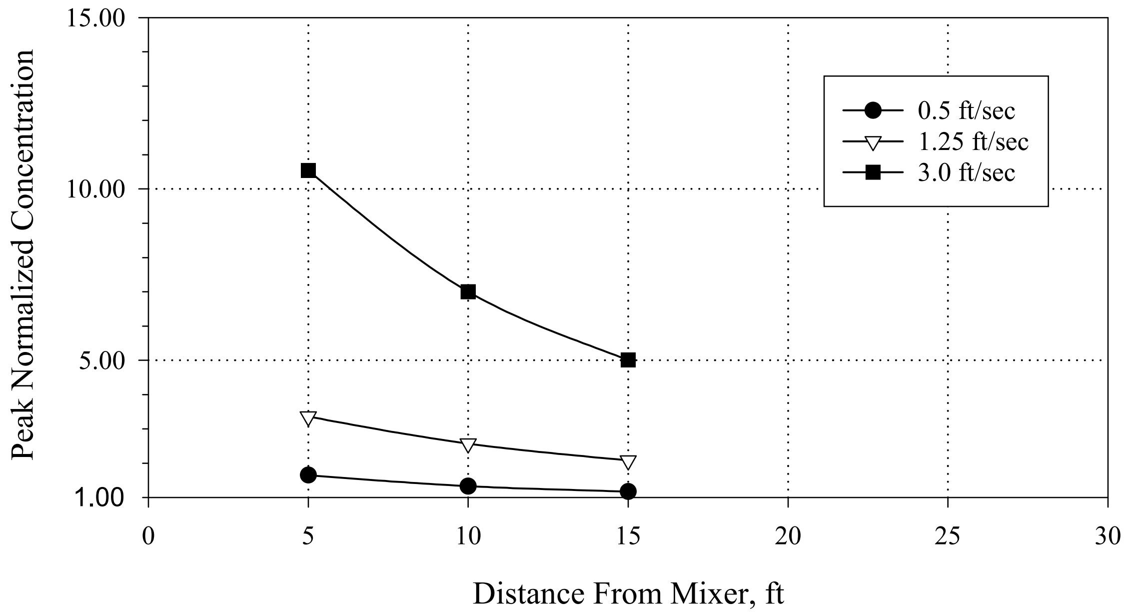


Figure 5-15: Example Of Maximum (Peak) Concentration Versus Distance From Mixer, 5 HP Mixer

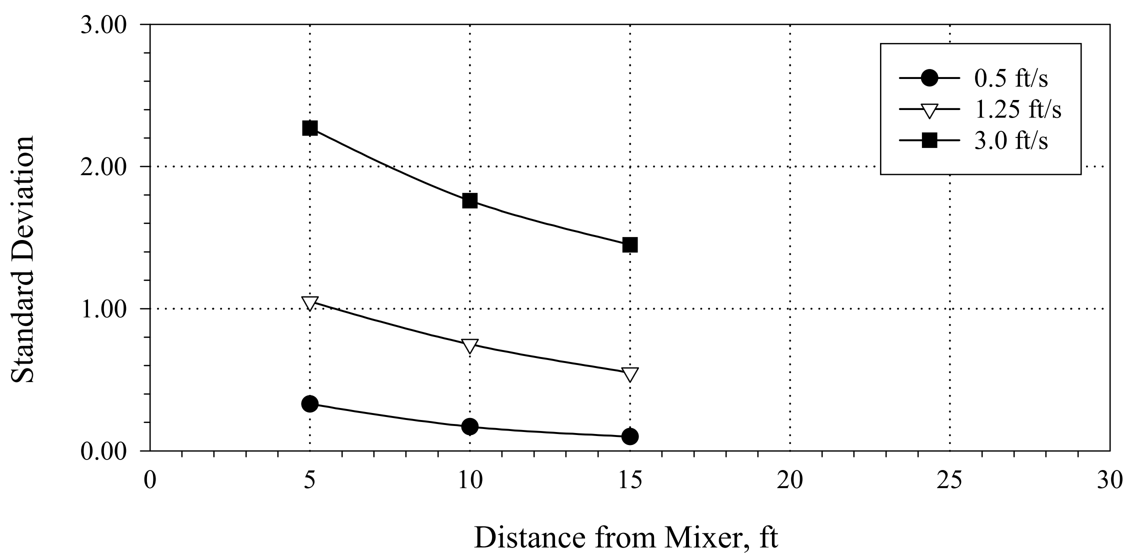


Figure 5-16: Example of Standard Deviation Of Normalized Concentration Versus Distance From Mixer

5.6 Summary of 5 HP Mixer Performance

Figure 5-17 summarizes the performance of the 5 HP mixer for all three velocities and brings together the three defining characteristics described in the sections above. These data are also contained in Table 5-1.

The tests conducted at the 3 ft/sec flume velocity (Tests 28, 29, and 30) were redone at the end of the test program when it was found that the tracer injection rate for these tests had been set incorrectly to the value corresponding to the 0.5 ft/sec flume velocity. Only the data from redone tests are presented in this report.

The average Mix Factor increased from 0.33 at a flume velocity of 3.0 ft/sec, to 0.67 at 0.5 ft/sec. Within each velocity, the plume size, indicated by the Mix Factor, increased on the average approximately 11% from the 5-ft to the 15-ft downstream location.

The Maximum (Peak) Normalized Concentration was highest at the 3.0 ft/sec flume velocity at the 5-ft downstream location, with a concentration 10.8 times the theoretical average. At each velocity, the maximum (peak) concentrations decreased significantly with distance from the mixer. At 0.5 ft/sec, the peak concentration decreased by 29% between the 5 ft and 15 ft location, while decreases observed at 1.25 ft/sec and3.0 ft/sec were 38% and 52%, respectively.

Table 5-1: Summary Of The 5 HP Mixer Performance

Mixer (HP)	Flume Velocity (ft/sec)	Sample Location (ft)	Mix Factor	Maximum (Peak) Normalized Concentration	Standard Deviation	Power (W)
5	0.5	5	0.65	1.64	0.33	4137
		10	0.68	1.32	0.17	4141
		15	0.68	1.16	0.10	4210
	1.25	5	0.43	3.33	1.04	4157
		10	0.49	2.55	0.74	4182
		15	0.46	2.07	0.54	4174
	3.0	5	0.28	10.75	2.31	4131
		10	0.35	7.14	1.80	4127
		15	0.36	5.11	1.48	4172

The standard deviation in the plume concentrations followed the trends of the maximum (peak) normalized values; decreasing quickly with increasing distances from the mixer. At the 0.5 ft/sec flow velocity, the standard deviation decreased by 70% between the 5 ft and 15 ft sample locations. The standard deviations for the 1.25 ft/sec and 3.0 ft/s tests decreased by 48% and 36%, respectively, between the 5-ft and 15-ft downstream locations.

Based on the consistency of the power calculations over the range of test conditions (listed in Table 5-1), it can be concluded that the mixer power requirements were not significantly affected by changes in flume velocity.

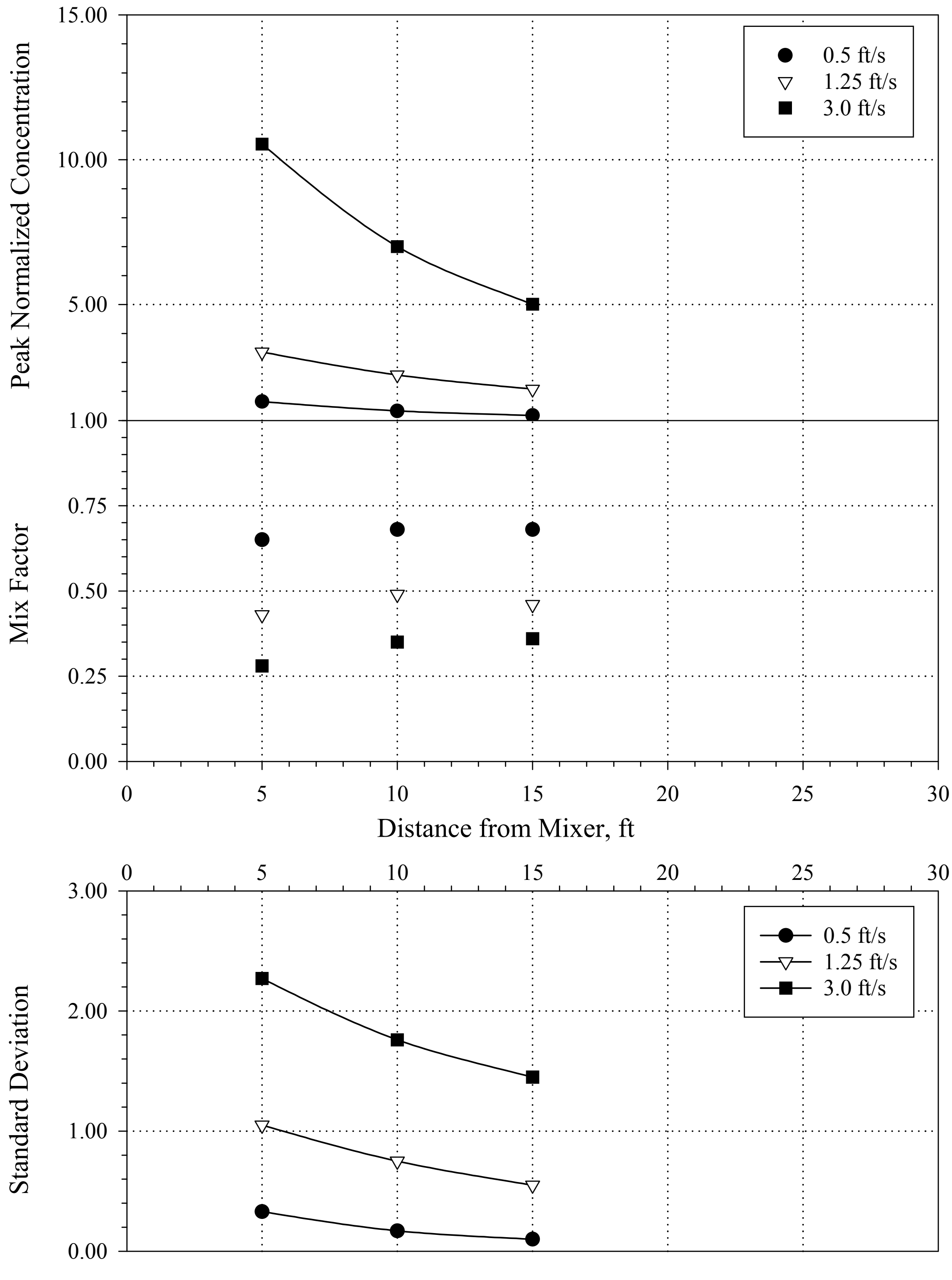


Figure 5-17: Summary Of The 5 HP Mixer Performance Data

5.7 Summary of 10 HP Mixer Performance

The 10 HP mixer performance is summarized graphically in Figure 5-18 and tabulated in Table 5-2. The average Mix Factor for the 10 HP mixer is increased by: 16%, 45%, and 15%, respectively, for the 0.5 ft/sec, 1.25 ft/sec, and 3.0 ft/sec flume velocities. This means that the plume, defined by the 0.95 isopleth, occupied approximately 16% more area than that of the 5 HP mixer for the low and high flume velocity and approximately 50% more area at the middle flume velocity.

The plume distribution plots for the 10 HP mixer at the 0.5 ft/sec flume velocity were different from the smaller 5 HP mixer. As shown in Figure 5-7, the highest concentrations were not in the middle of the flume, as they were for the smaller mixer. The likely cause of this behavior may be the size of the plume relative to the size of the flume (cross-section). This is discussed in more detail in Section 5.8.

Table 5-2: Summary Of The 10 HP Mixer Performance

Mixer (HP)	Flume Velocity (ft/sec)	Sample Location (ft)	Mix Factor	Maximum (Peak) Normalized Concentration	Standard Deviation	Power (W)
10	0.5	5	0.77	1.21	0.09	6980
		10	0.80	1.10	0.05	6960
		15	0.76	1.07	0.04	6908
	1.25	5	0.62	1.78	0.42	6963
		10	0.69	1.42	0.24	7015
		15	0.69	1.24	0.16	7050
	3.0	5	0.37	5.88	1.64	7077
		10	0.38	4.19	1.26	7166
		15	0.39	3.40	1.04	7144

The maximum (peak) normalized concentrations are lower for the 10 HP mixer compared to the 5 HP mixer. To quantify the performance improvement between the 5 HP and 10 HP mixer, one can compare the downstream location maximum (peak) normalized concentrations. At the 0.5 ft/sec velocity and 15 ft downstream, the 10 HP mixer maximum (peak) is 8% lower than that for the 5 HP mixer, indicating that only minor improvement is achieved by doubling the mixer power. At the 1.25 ft/sec and 3.0 ft/sec flume velocities, the maximum (peak) concentrations recorded 15 ft downstream with the 10 HP mixer were 40% and 33% lower, respectively, than those recorded for the 5 HP mixer.

As the mixing improves, the standard deviation in the plume concentration data decreases. At the downstream sampling location, the concentration profile of the 10 HP mixer produced 60%

to 70% lower standard deviation within the plume for the low and medium flume velocities. At the 3.0 ft/sec velocity, the deviation within the plume was 30% lower that the 5 HP mixer.

The power for the 10 HP mixer varied by less than 4% throughout the test data, indicating again that there was no significant effect of the flume velocity on power consumption.

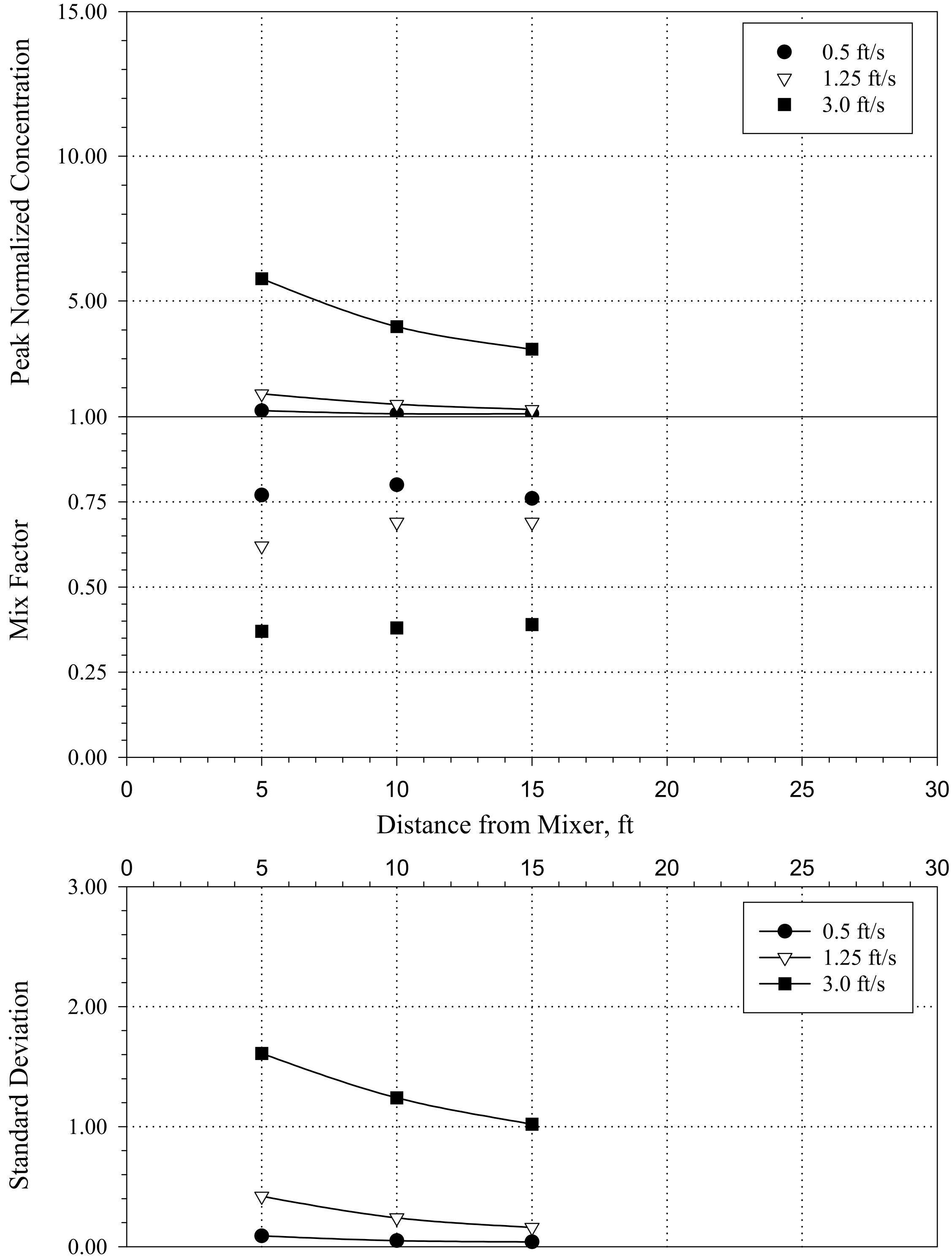


Figure 5-18: Summary of 10 HP Mixer Performance Data

5.8 Summary of 20 HP Mixer Performance

As discussed above, the 5 HP and 10 HP mixers showed a strong trend of decreasing mixing performance as the flume velocity increased; Mix Factor decreased with increasing velocity, and Maximum (Peak) values and Standard Deviation increased. In terms of these three parameters, the plume data for the 20 HP at the two lower flume velocities were identical within 10%. At the 3.0 ft/sec velocity, less mixing is indicated as evidenced by a lower Mix Factor and increased Maximum (Peak) value. These results are shown in Figure 5-19 and Table 5-3.

It is possible that the plume produced by the 20 HP mixer tends to spread further towards the boundaries of the test flume to the point of "saturating" the cross-section at the two lower velocities. The upstream region (5 ft and 10 ft sample locations) of the plume for this mixer at 0.5 ft/sec, had slightly lower concentrations in the center of the flume (see Figure 5-10). Similar lower center concentrations were also noted for the 10 HP mixer at the lowest flume velocity. It is possible that the mixer changes the flow distribution of the flume significantly. The basic design of the mixer is to propel flow radially, so the flow pattern downstream of the mixer may have a strong cross-channel (outward from center) component. With generally higher velocities in the center region of the flume, there is also additional flow in the center of the flume, compared to the regions close to the boundary. Assuming that the mixer drives the tracer throughout the section, the higher center flows would dilute the center concentrations and the tracer, in effect, would "pool" in the lower velocity regions around the perimeter of the flume.

The calculated Power for the 20 HP mixer showed a steady trend of increasing with flume velocity, drawing approximately 6% more power at the 3.0 ft/sec flume velocity than at the 0.5 ft/sec velocity.

Table 5-3: Summary Of The 20 HP Mixer Performance

Mixer (HP)	Flume Velocity (ft/sec)	Sample Location (ft)	Mix Factor	Maximum (Peak) Normalized Concentration	Standard Deviation	Power (W)
20	0.5	5	0.74	1.14	0.07	13820
		10	0.84	1.04	0.03	13855
		15	0.92	1.00	0.05	13955
	1.25	5	0.79	1.39	0.17	13998
		10	0.86	1.19	0.09	14233
		15	0.92	1.10	0.05	14417
	3.0	5	0.44	3.30	1.00	14934
		10	0.46	2.50	0.70	14511
		15	0.46	2.09	0.54	14858

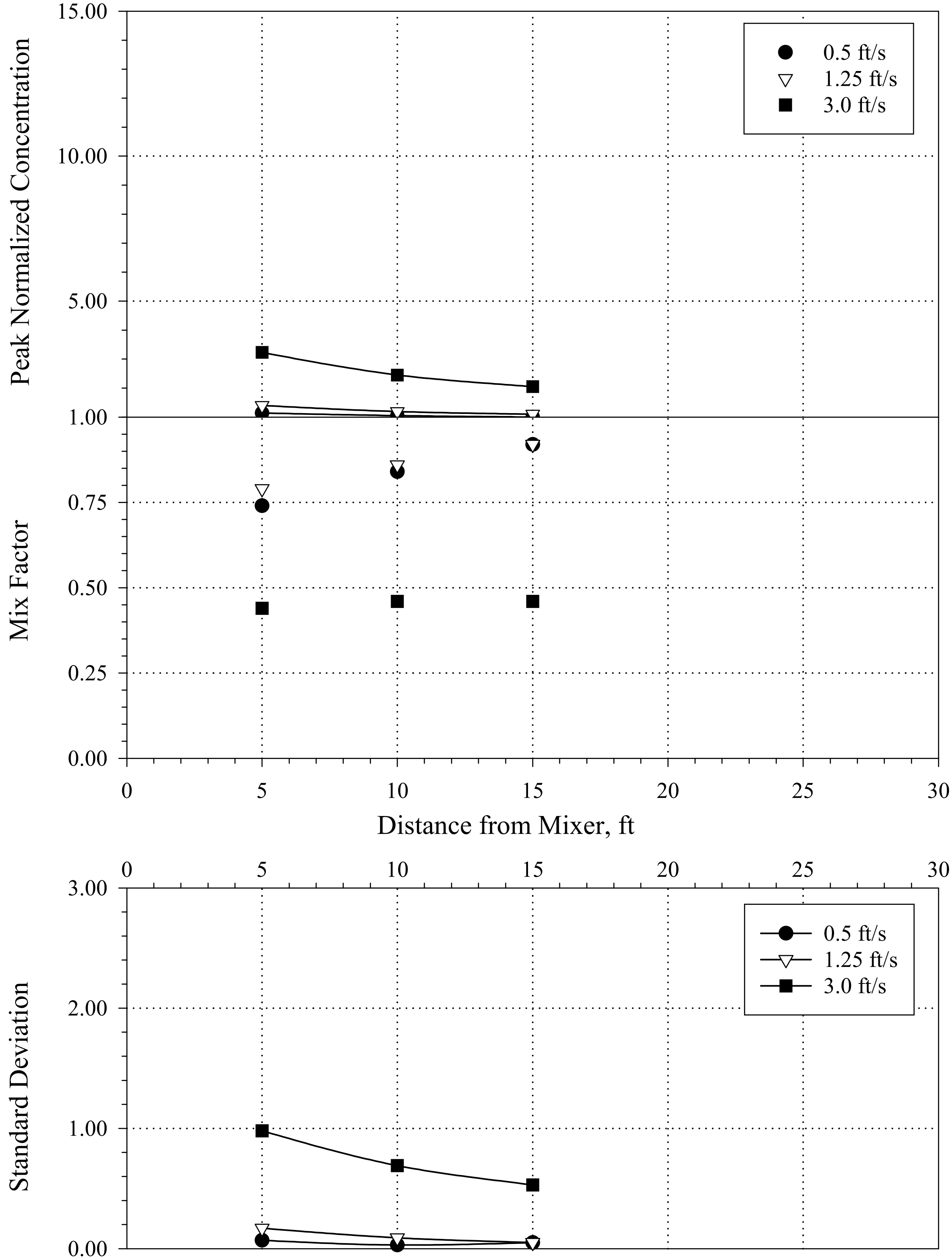


Figure 5-19: Summary of 20 HP Mixer Performance Data

5.9 General observations

Application of the Mix Factor predicts the plume area, as the Mix Factor multiplied by the test flume area (7 ft × 7 ft = 49 ft^2) gives the plume area for the 0.95 isopleth. For cases where the plume (area) is much smaller than the flume (e.g., about 0.5 or less), the results were independent of the test flume used, and vice versa. For the former case, the 0.95 isopleth may be considered to be circular.

The application of the standard deviation allows a fuller description of the distribution of concentrations above the theoretical uniform concentration isopleth. For a normal distribution, plus and minus one standard deviation from the 1.0 isopleth would include 68% of the data, plus and minus two standard deviations includes 95% of the data, and plus and minus three standard deviations include 99.1% of the concentration data (i.e., almost the peak high and low values). For most measured plumes, the distribution is not normal but is highly skewed; so equal percentages of the data do not denote equal changes in concentration above and below 1.0. The value below 1.0 is limited by zero (0.0), but the value above 1.0 is given by the maximum value. Therefore, the standard deviation is used only to give an indication of concentration values above 1.0.

For example, a test condition giving a Mix Factor of 0.50, a maximum (peak) normalized concentration of 3.5 and a standard deviation of 1.2 indicates the area of the uniform 1.0 concentration isopleth is 0.5 49 ft^2 = 24.5 ft^2, has a central peak value of 3.5 and has 95% of all concentration data between approximately zero and [1.0 + 2 (1.2)] = 3.4.

Based on the test results, the following conclusions are drawn regarding the relative performance of each mixer:

- As the flume velocity increased, the performance of the mixer decreased. For example, at 0.5 ft/sec flume velocity, the Mix Factor and the maximum (peak) normalized concentrations were 0.68 and 1.16, respectively, for a 5 HP mixer 15 ft away from the mixer. For the same mixer at the same location, a flume velocity of 3 ft/sec resulted in a Mix Factor and maximum (peak) normalized concentrations of 0.36 and 5.11, respectively, indicating a decrease of the Mix Factor by about 50% and a nearly five fold increase of the maximum (peak) concentration.

- For higher flume velocities, a larger HP mixer performed better. For example, at 3 ft/sec flume velocity, the Mix Factor and maximum (peak) normalized concentration at 15 ft downstream for a 20 HP mixer were 0.46 and 2.09, respectively, compared to 0.36 and 5.11, respectively, for a 5 HP mixer. The standard derivation of concentration variations for a 20HP mixer was almost one half of that for a 5 HP mixer.

- Mixing is observed to increase with distance from the mixer, more so for a higher HP mixer compared to the lower HP mixer. For example, at 1.25 ft/sec velocity, the Mix Factors changed from 0.43 to 0.49 as the distance increased from 5 ft to 10 ft downstream for a 5 HP mixer, while the corresponding change was from 0.79 to 0.92 for a 20 HP mixer. The maximum (peak) normalized concentrations and standard deviations were less at 10 ft downstream compared to 5 ft downstream.

- The 20 HP mixer produced roughly identical results at the 0.5 and 1.25 ft/sec flume velocities, with identical Mix Factors of 0.92 and Maximum (Peak) Concentrations of 1.00 and 1.10, respectively, at 15 ft downstream from the mixer (impeller). The similarity of these data, despite the different flume velocity, may have been due to the rapid spreading of the mixer plume toward the boundaries of the flume, thus "saturating" the flow. At a flume velocity of 3 ft/sec, the corresponding Mix Factor was 0.46 and the Maximum (Peak) concentration was 2.09 times the average.

5.10 Determining Mean Velocity Gradient

5.10.1 An Approach to Calculating Mean Velocity Gradient (G)

The data collected through this verification testing identifies parameters related to mechanical induction mixing, namely horsepower and flow velocity and their effects on the volume of process water influenced by the mixers.

Many engineers use the mean velocity gradient, or G as a measure of the mixing intensity needed for a particular mixing application. White (1992), proposed a G of 700/sec as a rule of thumb. An example of this calculation is illustrated in Figure 5-20 and explained below.

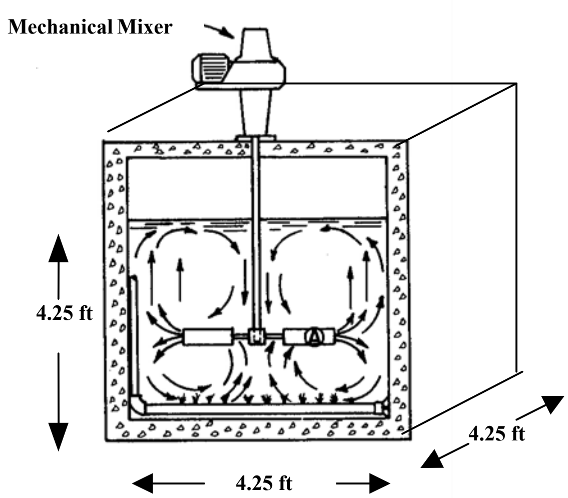


Figure 5-20 Example of Defined Mixing Chamber

Using Equation 1-3, the mean velocity gradient, G, can be calculated for the mixing chamber pictured in Figure 5-20 while assuming a uniform mix is achieved with 3 horsepower mixer.

$$G = \sqrt{\frac{3hp \times 550\, ft \bullet lb/\sec/hp}{0.000027 lb \bullet \sec/ft^2 \times 77\, ft^3}} = 950/\sec$$

This example shows how G is calculated when there is defined volume (in this case 77 ft^3) in which the mixer is operating and providing a uniform mix. The theoretical G for this example is 950/sec. Considering White's recommendation that a G value of 700/sec is desired, the 3-HP mixer may be slightly oversized for this application.

When designing a mixing system in an open channel as often done in WWF treatment facilities, the volume of the mixing zone is a function of the boundary conditions (i.e. channel walls), in addition to mixer horsepower and flow velocity.

In order to calculate G for the purposes of this verification, criteria must be established for defining the volume of the mixing zone in the open channel. A description of this criterion is included below. It is important to note that these criteria and the related assumptions are based on the site-specific conditions and results of this verification testing, and may not translate exactly to other induction mixer applications.

5.10.2 Criteria for Defining a Mixing Zone

For the purposes of this verification, the volume of the mixing zone used to calculate G is defined as the smallest volume in which the mixer meets an established mixing criterion. The mixing criteria are established as described here.

Mixing Criteria I: cross-sectional mixing zone extent

The cross-sectional boundary of the mixing zone is based on the extent of the 0.5 normalized tracer concentration. The normalized tracer concentration is the theoretical tracer concentration if the tracer were instantaneously dispersed over the entire cross section of the channel. There were two reasons for selecting a normalized tracer concentration of 0.5. The first being that if two mixers were required, their mixing zones could be overlapped at the 0.5 concentration for a cumulative affect equivalent to a concentration of 1.0. The second reason being that half the theoretically applied dose at the extents of the mixing zone is assumed to provide sufficient bacteria reductions. Under such a mixing condition bacteria reductions in the center of the mixing zone where the concentrations are highest would likely exceed the needed bacteria reductions, while the bacteria reductions at the extents would likely be less than needed. It is important to note that this assumption was made for the purpose of calculating G for this verification test, and may not relate to site-specific bacteria requirements.

Mixing Criteria II: downstream mixing zone extent

The downstream boundary of the mixing zone is based on the channel length, beyond which the Mix Factor ceases to improve by more than 5%. The Mix Factor is the percent of the total cross-sectional channel area that has experienced a normalized tracer concentration of 1.0. This criteria was made based on the assumption that volume of the mixing zone could not be larger than the volume of water directly affected by the mixer. In this verification report, the energy imparted by the mixer to disperse tracer appeared to diminish after 10 feet downstream of the mixer. This is not to say that tracer stopped dispersing at 10 feet, but rather the energy imparted by the mixer no longer played a significant role for the dispersion of tracer. After 10 feet the tracer continued to disperse, but at a much slower rate, and probably as a result of the passive mixing provided by the kinetic energy of the process water, than the active mixing provided by the induction mixer.

To calculate G in an open channel using the data generated by this ETV verification, the smallest mixing zone volume can be defined as:

- The shortest channel length required to meet the cross-sectional mixing zone extent criteria at the channel wall (Criteria I); or

- The shortest channel length in which the direct effects of the mixer are no longer considered significant (Criteria II).

The flow diagram presented in Figure 5-21 is used to select the cross-sectional area and length of channel that defined the smallest volume for each mixer at each flow velocity. Using this approach, a mixing zone volume is estimated for each size mixer at each velocity. The mixing zone volume is then used in Equation 1-3 to calculate G.

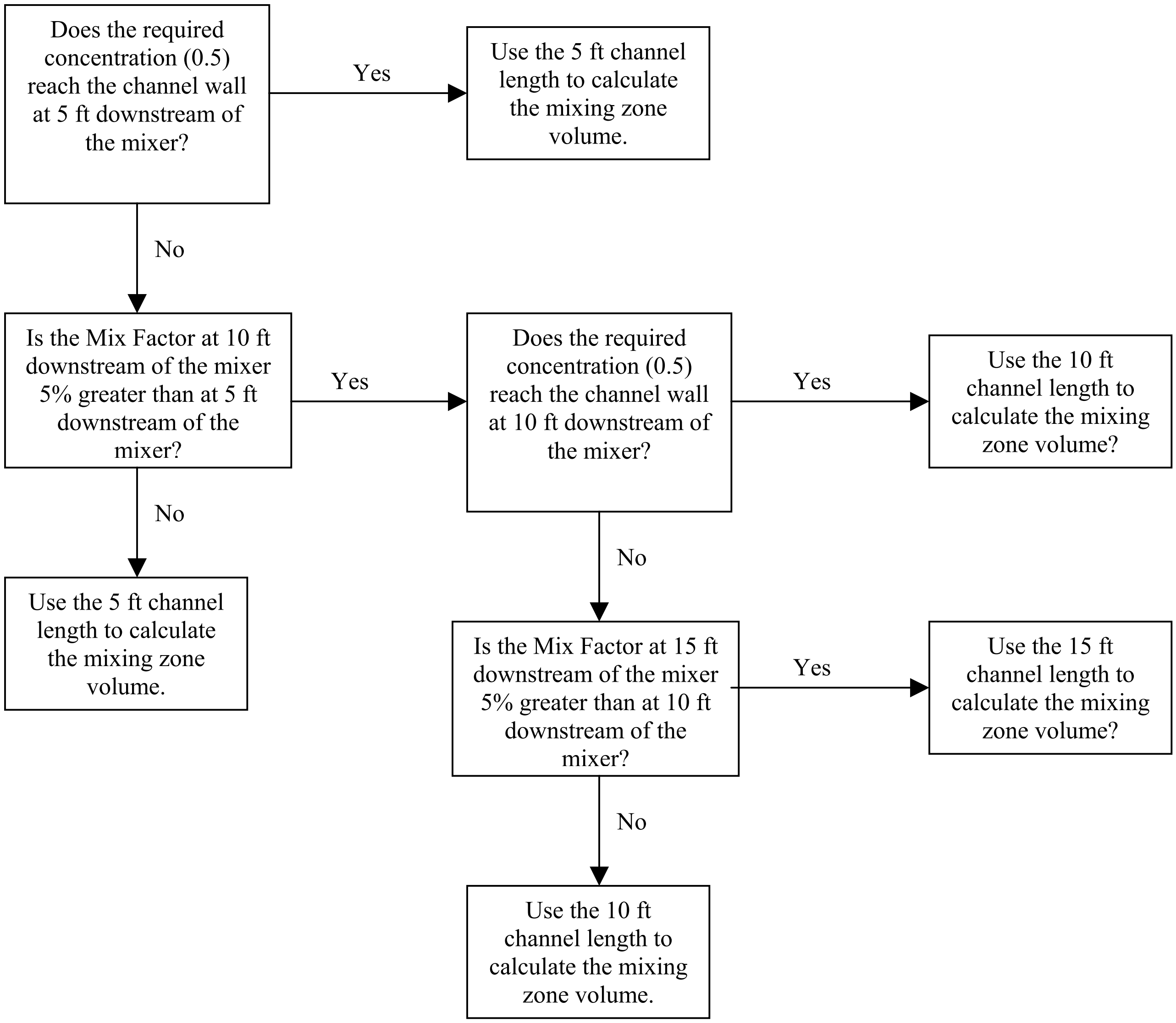


Figure 5-21: Decision Flow Diagram for Selecting Smallest Mixing Zone Volume

5.10.3 Calculated G Values

Using the assumptions and criteria defined above, G values were calculated for each of the three mixer sizes at each of the three flow velocities under which testing was conducted. The calculated G values for each are shown in Table 5-4, along with the distance downstream mixing criteria and the mixing zone volume determinations used to calculate G.

At a flow velocity of 0.5 ft/sec, each mixer met the cross-sectional mixing criteria at the channel wall within 5 feet. Conversely, at a flow velocity of 3.0 ft/sec, none of the mixers met the cross-sectional mixing criteria at the channel wall within 15 feet. It is important to note that the minimum sampling location downstream of the mixer was 5 ft. In many cases the mixers met the required dispersion in less than 5 ft, but due to sampling limitations a distance of less than 5 ft was not possible. It is also important to note that mixing continued to improve after the 5 ft location, but the mixing requirement was met at or before the 5 ft location and improvements thereafter were due to the passive mixing of process water.

Table 5-4: Calculated G Values

Flow Velocity Condition: 0.55 ft/sec				
Mixer (HP)	Distance Downstream Mixing Criteria (ft)	Cross-Sectional Area (ft^2)	Resulting Mixing Zone Volume (ft^3)	Calculated G (1/sec)
5	5	49 (7' x 7')(1)	245	645
10	5	49 (7' x 7')(1)	245	912
20	5	49 (7' x 7')(1)	245	1290
(1): For each mixer, the 0.5 dye concentration reaches the channel wall within 5 ft. Therefore, the cross-sectional mixing extent (i.e. the smallest volume) was delineated by the channel wall at a distance of 5 ft.				

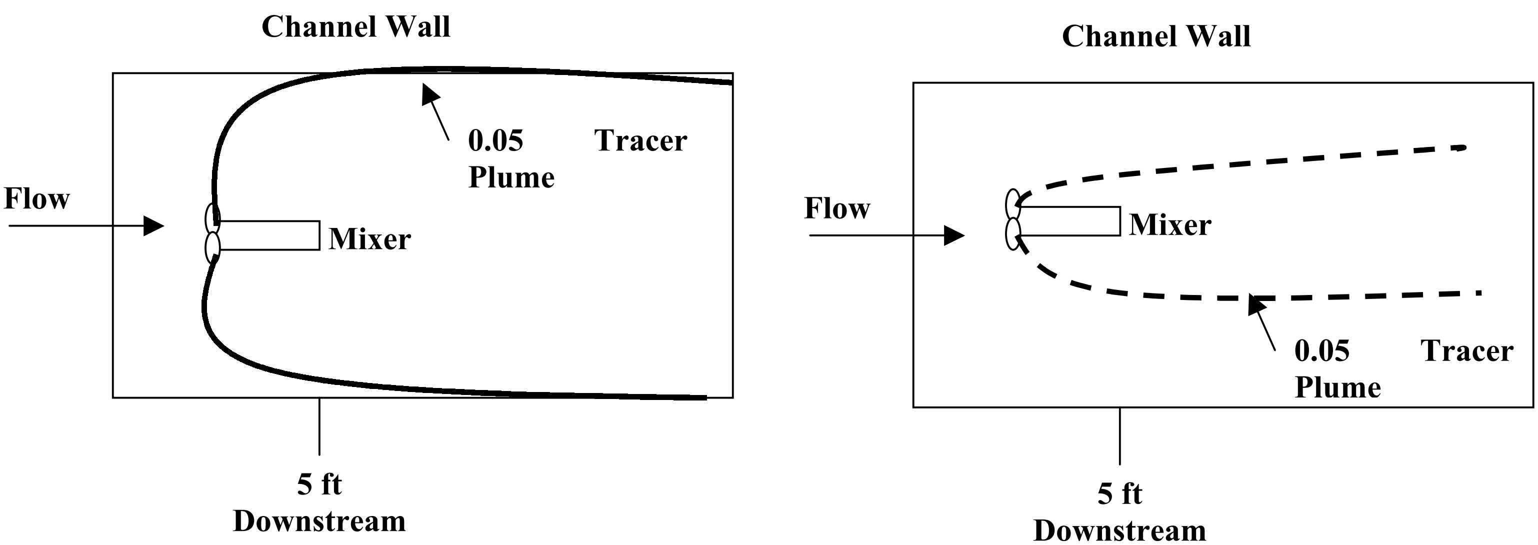
Flow Velocity Condition: 1.2 ft/sec				
Mixer (HP)	Distance Downstream Mixing Criteria (ft)	Cross-Sectional Area (ft^2)	Resulting Mixing Zone Volume (ft^3)	Calculated G (1/sec)
5	10	28 (6 ft diameter)(1)	280	603
10	5	49 (7' x 7')(2)	245	912
20	5	49 (7' x 7')(2)	245	1290
(1): For the 5 HP mixer, the 0.5 dye concentration did not reach the channel wall, and the Mix Factor ceased to improve after 10 ft. Therefore, the cross-sectional mixing extent (i.e. the smallest volume) was delineated by the 0.5 dye concentration plume at a distance of 10 ft. (2): For the 10 HP and 20 Hp mixers, the 0.5 dye concentration reaches the channel wall within 5 ft. Therefore, the cross-sectional mixing extent (i.e. the smallest volume) was delineated by the channel wall at a distance of 5 ft.				

Flow Velocity Condition: 3.0 ft/sec				
Mixer (HP)	Distance Downstream Mixing Criteria (ft)	Cross-Sectional Area (ft^2)	Resulting Mixing Zone Volume (ft^3)	Calculated G (1/sec)
5	10	20 (5 ft diameter)(1)	200	714
10	5	24 (5.5 ft diameter)(2)	120	1303
20	5	28 (6 ft diameter)(2)	140	1706
(1): For the 5 HP mixer, the 0.5 dye concentration did not reach the channel wall, and the Mix Factor ceased to improve after 10 ft. Therefore, the cross-sectional mixing extent (i.e. the smallest volume) was delineated by the 0.5 dye concentration plume at a distance of 10 ft. (2): For the 10 HP and 20 Hp mixers, the 0.5 dye concentration did not reach the channel wall, and the Mix Factor ceased to improve after 5 ft. Therefore, the cross-sectional mixing extent (i.e. the smallest volume) was delineated by the 0.5 dye concentration plume at a distance of 5 ft.				

5.10.4 Discussion of G Calculations

The calculated G values shown in Table 5-4 are consistent with the definition of mixing intensity as defined by Equation 1-3; as horsepower increases or volume decreases, G increases. The following observations regarding G can be drawn from these calculations:

There are two types of mixing zones evident from the review of the data. One is the mixing zone delineated by the channel walls as depicted in Figure 5-22A. The other is the mixing zone delineated by the tracer plume as depicted in Figure 5-22B. In Table 5-4, a cross-sectional area of 49 ft^2 (7 ft x 7 ft) signifies the mixing zone is delineated by the channel walls.



A. Channel Wall-Delineated Mixing Zone, Plan View.

B. Plume-Delineated Mixing Zone, Plan View.

Figure 5-22 : Mixing Zone Patterns

5.10.4.1 Channel Wall-Delineated Mixing Zone

When the channel wall delineates the mixing zone, as mixer horsepower increases and volume remains the same, G increases. For example, during this verification testing each mixer met the required mixing criteria before the 5 ft sampling location at 0.5 ft/sec. Therefore, the mixing zone volume was defined by the cross-section area of the channel and the distance 5 ft downstream of the mixer. As presented in Table 5-4, G increases as horsepower increases. This is analogous to the example illustrated in Figure 5-20 and Equation 1-1, where G increases as horsepower increases in a defined mixing zone volume.

5.10.4.2 Transition from Channel Wall-Delineated Mixing Zone to Plume-Delineated Mixing Zone

The mixing zone pattern changes at higher velocities due to the higher kinetic energy of the process water working against the mixer energy to disperse the tracer. At higher velocities the tracer plume of 0.5-tracer concentration delineates the mixing zone, and not the channel walls. This is because the higher velocities tend to "concentrate" the mixer's energy within a smaller volume. This in effect produces a higher G value, but it is applied over a smaller volume of the process water, which may not be an efficient use of horsepower (i.e. energy).

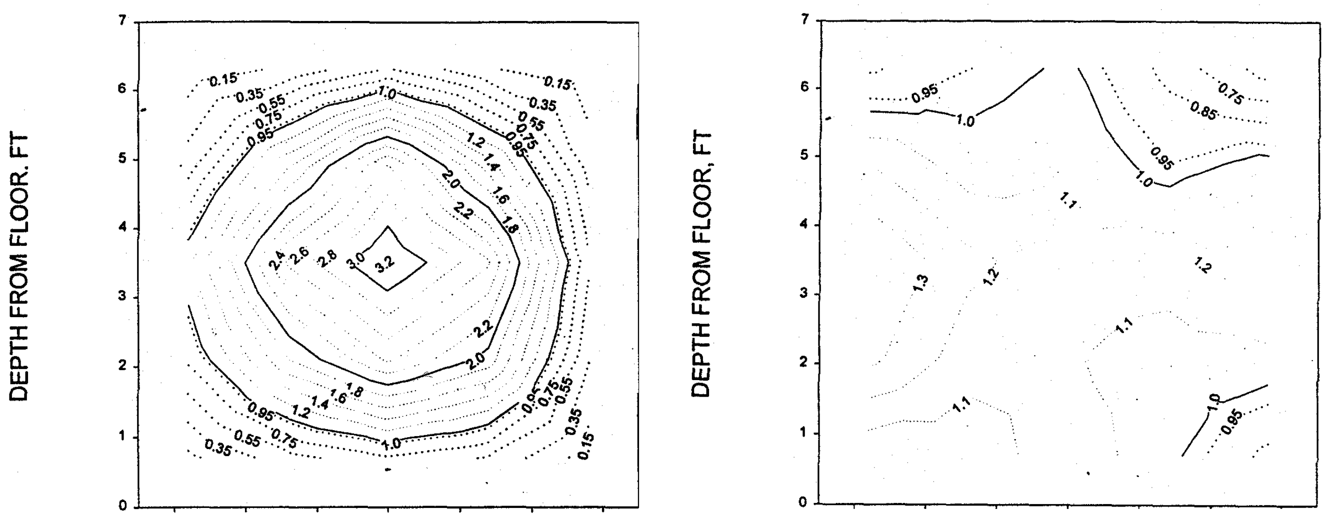
This transition between mixing patterns occurs at 1.2 ft/sec for the 5-HP mixer and at 3.0 ft/sec for the 10-HP and 20-HP mixers. Comparisons of G between the two mixing zone patterns should not be made because the volumes are determined differently.

5.10.4.3 Plume-Delineated Mixing Zone

When the tracer plume delineates the mixing zone, as velocity increases and the size of the mixer remains the same, the volume of mixing zone decreases and therefore the G increases. Although the G value increases, it does not imply a better mix. It simply means that the same horsepower input is being applied over a smaller volume. For example, at 1.2 ft/sec, the 5-HP influences a cross-sectional area of 28 ft^2 at a channel length of 10 feet downstream from the mixer. This cross-sectional area decreases to 20 ft^2 at 3.0 ft/sec, and therefore the calculated G increases. Again, this does not imply a better mix, but rather the horsepower being applied over a smaller volume.

5.11 Assessing the Uniformity of Mix

While the data from the verification tests produce G values that exceed the accepted value for superior mixing, they alone do not characterize the volume and uniformity of the mixing zone. For example, as illustrated in Figure 5-23, the 20-HP mixer at 1.2 ft/sec provides a much more uniform mix than at 3.0 ft/sec, even though the G value at 3.0 ft/sec is greater, 1,706/sec versus 1,290/sec. This example illustrates the importance of not only relying on G values, but rather to consider the volume of the mixing zone and the uniformity of the mix within this zone.



Test 46: 20 HP at 5 ft & 3.04 ft/sec Test 51: 20 HP at 5 ft & 1.23 ft/sec

Figure 5-23 Comparison of Uniformity of Mix at Different Flume Velocities

The uniformity of the mixing zone can be depicted by the variance within the tracer concentrations throughout the cross-section are of the plume. For the purpose of this verification test the standard deviation of the tracer concentration as calculated for each mixer is directly related to the uniformity of the mix. A more uniform mix is indicated by a lower standard deviation. For this verification test a standard deviation of less than 0.5 appears to provide a sufficient uniform mix. When using a standard deviation of 0.5, the maximum tracer concentration is approximately twice that of the 1.0 normalized tracer concentration. Establishing a uniform mix is important so that disinfection chemicals are used efficiently; it is not efficient to have a mixing zone where a portion of the volume has a concentration of disinfectant several times greater than required for the application.

5.12 Sizing of Mixers for Disinfection Applications

The mixing zone and the uniform mix criterion presented in Sections 5.10 and 5.11 can assist in determining an appropriate mixer sizing criteria for a given flow condition. By determining the smallest size of mixer that satisfies the mixing criteria and the desired minimum G value of 700/sec, an appropriate minimum ratio of horsepower to flow (MGD) can be established.

5.12.1 Flow condition #1: 0.5 ft/sec

The 5-HP mixer meets the mixing criteria at a flow velocity of 0.5 ft/sec within a 7 ft x 7 ft open channel assuming a required G = 700/sec. Both the mixing zone and the uniform mix criteria are met within 5-feet downstream of the mixer. This equates to a horsepower to MGD ratio of 0.31.

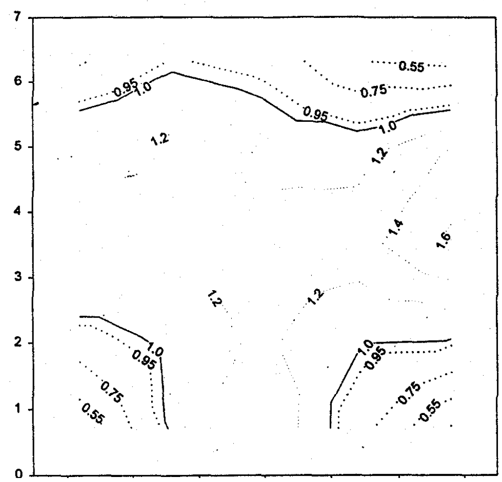


Figure 5-24: Test 34: 5 HP at 5 ft & 0.54 ft/sec

5.12.2 Flow Condition #2: 1.2 ft/sec

The 5-HP mixer almost meets the mixing criteria at 1.2 ft/sec within a 7 ft x 7 ft open channel and 15 feet downstream. The actual cross-section area that meets the criteria is 36 ft^2. Based on this cross-sectional area, the horsepower to MGD ratio is 0.18.

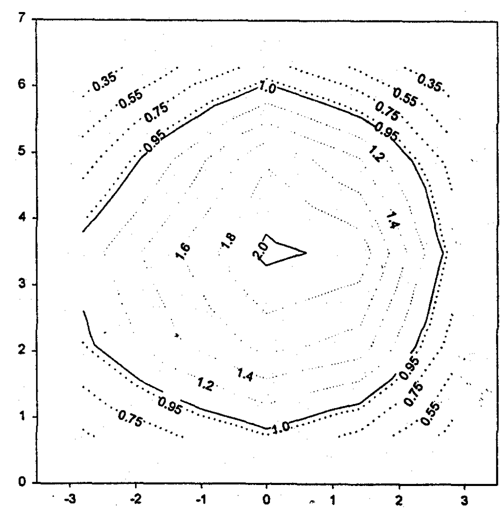


Figure 5-25: Test 31: 5 HP at 15 ft & 1.2 ft/sec

The 10-HP mixer meets the mixing criteria at a flow velocity of 1.2 ft/sec within a 7 ft x 7 ft open channel assuming a required G = 700/sec. Both the mixing zone and the uniform mix criteria are met within 5 ft downstream of the mixer. This equates to a horsepower to MGD ratio of 0.26.

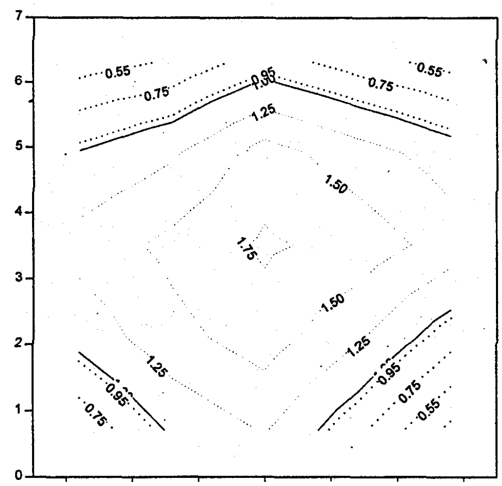


Figure 5-26: Test 40: 10 HP at 5 ft & 1.2 ft/sec

5.12.3 Flow condition #3: 3.0 ft/sec

The 10-HP mixer does not meet the criteria at 3.0 ft/sec within a 7 ft x 7 ft open channel and 15 ft downstream. The actual cross-section area that meets the mixing zone extent criteria is 24 ft^2 (5.5 ft in diameter). Based on this cross-sectional area, the horsepower to MGD ratio is 0.22.

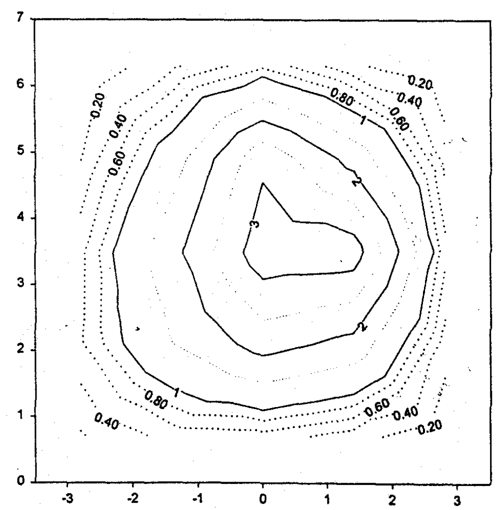


Figure 5-27 Test 45: 10 HP at 15 ft & 3.0 ft/sec

The 20-HP mixer almost meets the criteria at 3.0 ft/sec within a 7 ft x 7 ft open channel. Both the mixing zone and the uniform mix criteria are almost met within 15 ft downstream of the mixer, and the G value of 700/sec is exceeded. The actual cross-section area that meets the mixing zone extent criteria is 36 ft^2. Based on this cross-sectional area, the horsepower to MGD ratio is 0.28.

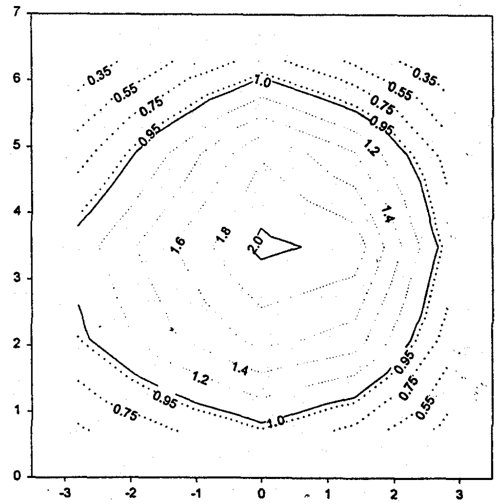


Figure 5-28: Test 48: 20 HP at 15 ft & 3.0 ft/sec

5.12.4 Mixer Sizing Criteria

In summary, the data indicated a mixer sizing criteria of between 0.22 and 0.31 HP/MGD resulted in mixing sufficient for disinfection for mixing applications in the 7 ft x 7 ft open channel with flow velocities between 0.5 and 3.0 ft/s. The data also indicated a break point in the data at a flow velocity of 1.25 ft/s, where at higher velocities the influence of higher horsepower on the size of the mixing zone volume has diminishing returns. It is clear that flow velocity significantly influences the ability of the mixers to effectively disperse tracer. Therefore, expected range of flow velocities must be considered when selecting an appropriate sized mixer during the design of open channel mixing facilities.

6 Quality Assurance

Testing was conducted in accordance with the Quality Assurance Project Plan (QAPP) contained in the VTP. The QAPP was based on the quality assurance program of Alden Research Laboratory, which addressed test plan development, data retrieval, data reduction, reporting, and test review procedures. In general testing proceeded as planned and on schedule with what was presented in the VTP. Adherence to the quality assurance plan revealed that an error occurred with respect to the tracer injection rate for three consecutive tests on a single day. During an on-site review of concentration data from Test 28, 29, and 30, it was noted that the concentrations were well below the anticipated values. A subsequent review of the appropriate Mixer Testing Data Sheets clearly showed that the tracer injection rate had been set incorrectly for those tests and was outside the limits set in the VTP. This prompted a repeat of these tests with the correct injection rate. Data from the repeated tests are presented in this Verification Report.

No further errors or deviations from the VTP were observed during the duration of the test.

6.1 Uncertainty of Measurements (Bias and Precision)

Two areas of measurement that were fundamental to data quality were flume velocity and tracer concentration. Measurement of each of these parameters requires a variety of instruments and analytical procedures. The calculation of estimate of uncertainty associated with these measurements was derived from “ANSI/ASME PTC 19.1-1985 Measurement Uncertainty, A Supplement to the ASME Performance Test Codes.” Appendix C of this report contains a detailed uncertainty analysis for the determination of tracer concentration and flume velocity. In summary, the estimate of uncertainty in the determination of tracer concentration sampled downstream of the induction mixers was 2.9 percent at the 95% confidence interval. The overall uncertainty in the measurement of flume velocity was 3.3%.

6.2 Repeat Test Data

In accordance with the quality assurance project plan in the VTP, one test for each size mixer was repeated in full. The repeat tests are identified in Table 4-1 by an "RT" added to the test number. The concentration data from the repeat tests were plotted for comparison to the original test data, as shown in Figures 6-1, 6-2, and 6-3 for Tests 34, 40, and 52. Visually, the size, location, and general shapes of the repeat test isopleths are a close match to the original results. This observation was confirmed by comparing the calculated values of: Mix Factor, Maximum (Peak) Normalized Concentration, and Standard Deviation. These calculated values from the repeat test data agreed with those from the corresponding original tests within 3%, except the Mix Factor of Test 52; where the repeat test Mix Factor was approximately 8% higher than the original result. The deviation in the Mix Factor for Test 52 may be explained by the fact the distribution was fairly flat, and therefore, a slight change in the measured concentrations near the mean can shift the 0.95 isopleth and, in turn, affect the area which is measured to calculate the Mix Factor. The repeat tests were incorporated into the test program to provide a check on the repeatability of the mixer performance and the methods used to evaluate performance. They were not intended to provide for a statistically valid analysis of the study data. The results of the repeat tests suggest that there were not significant changes in mixer performance or test procedures from one day of testing to another.

6.3 Repeat Concentration Sample Analysis

Sample from two selected tests (Test 35 and Test 43) were re-analyzed for tracer concentration within 24 hours of the original analysis in order to assess the performance of the fluorometer and to provide a check of the analyses process, from handling of the sample bottles to calibrating the fluorometer. In order to re-analyze the samples on a different day, with (possibly) different operating temperatures of the fluorometer and samples, the fluorometer was recalibrated using the appropriate calibration sample set. The tests of the repeat analysis are identified with the letter "RA" added to the test number.

The concentration distribution plots and the calculated values for Tests 35 and 43 are shown in Figures 6-4 and 6-5, respectively. For the two re-analyzed tests, the Maximum (Peak) Normalized Concentration repeated within 4% and 1%, respectively, and the Standard Deviations repeated within 1%. These results suggest that the repeatability of sample analysis procedures were suitable for the data quality objectives of the testing program.

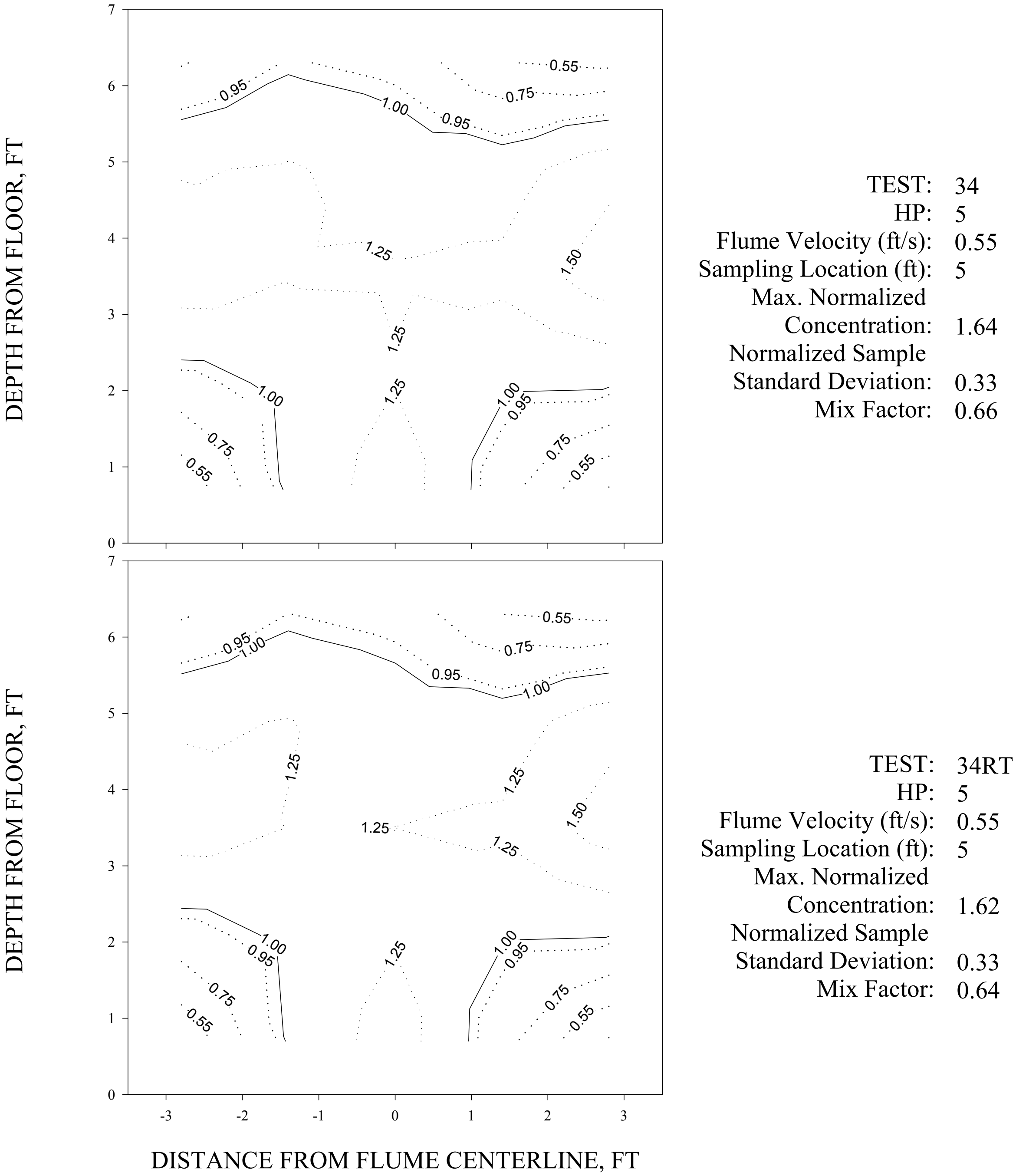


Figure 6.1: Comparison of Original and Repeat Testing—Non-Dimensional Concentration Distribution For The 5 HP Mixer at 0.5 ft/sec Flume Velocity

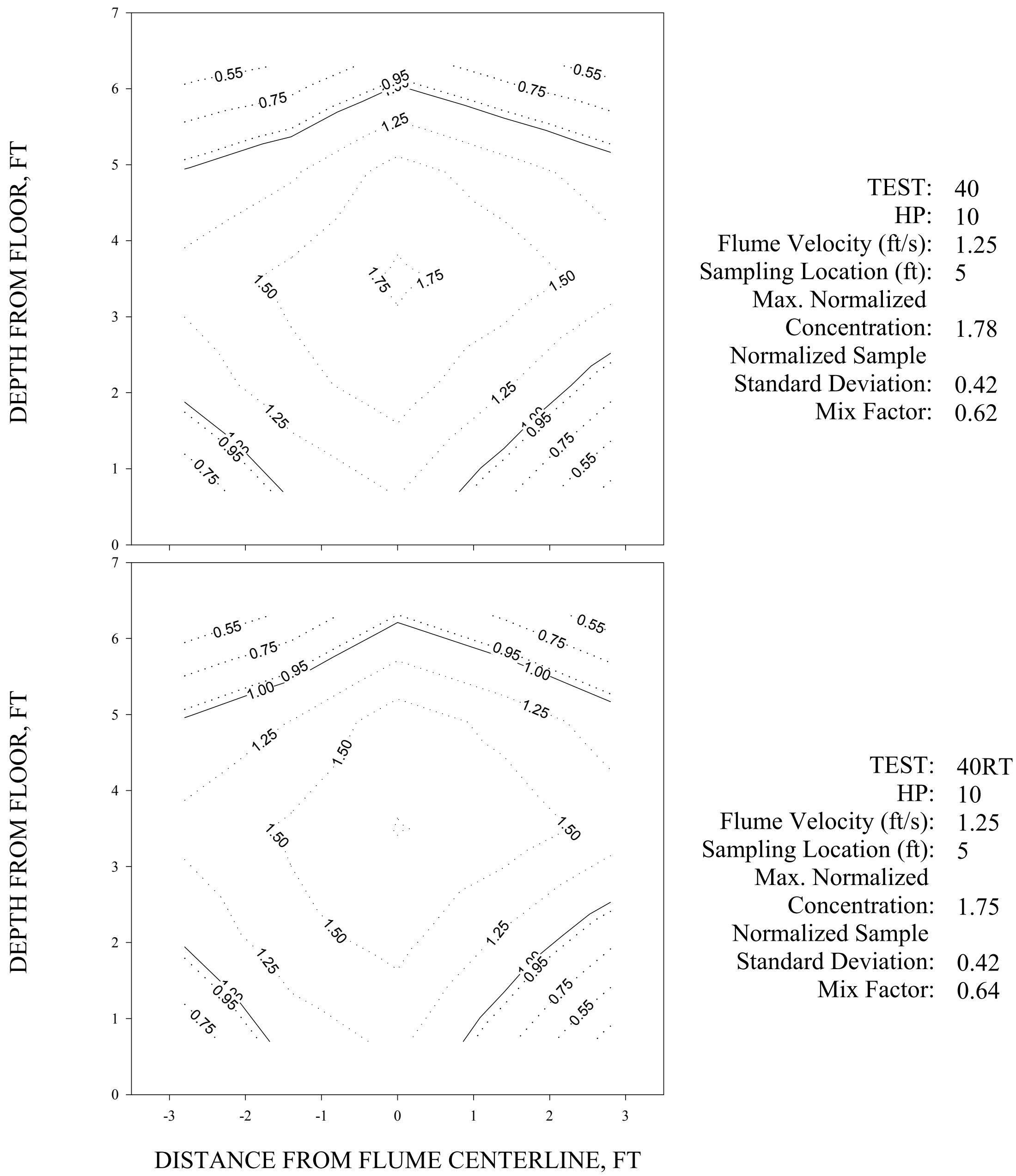


Figure 6.2: Comparison of Original and Repeat Testing—Non-Dimensional Concentration Distribution For The 10 HP Mixer at 1.25 ft/sec Flume Velocity

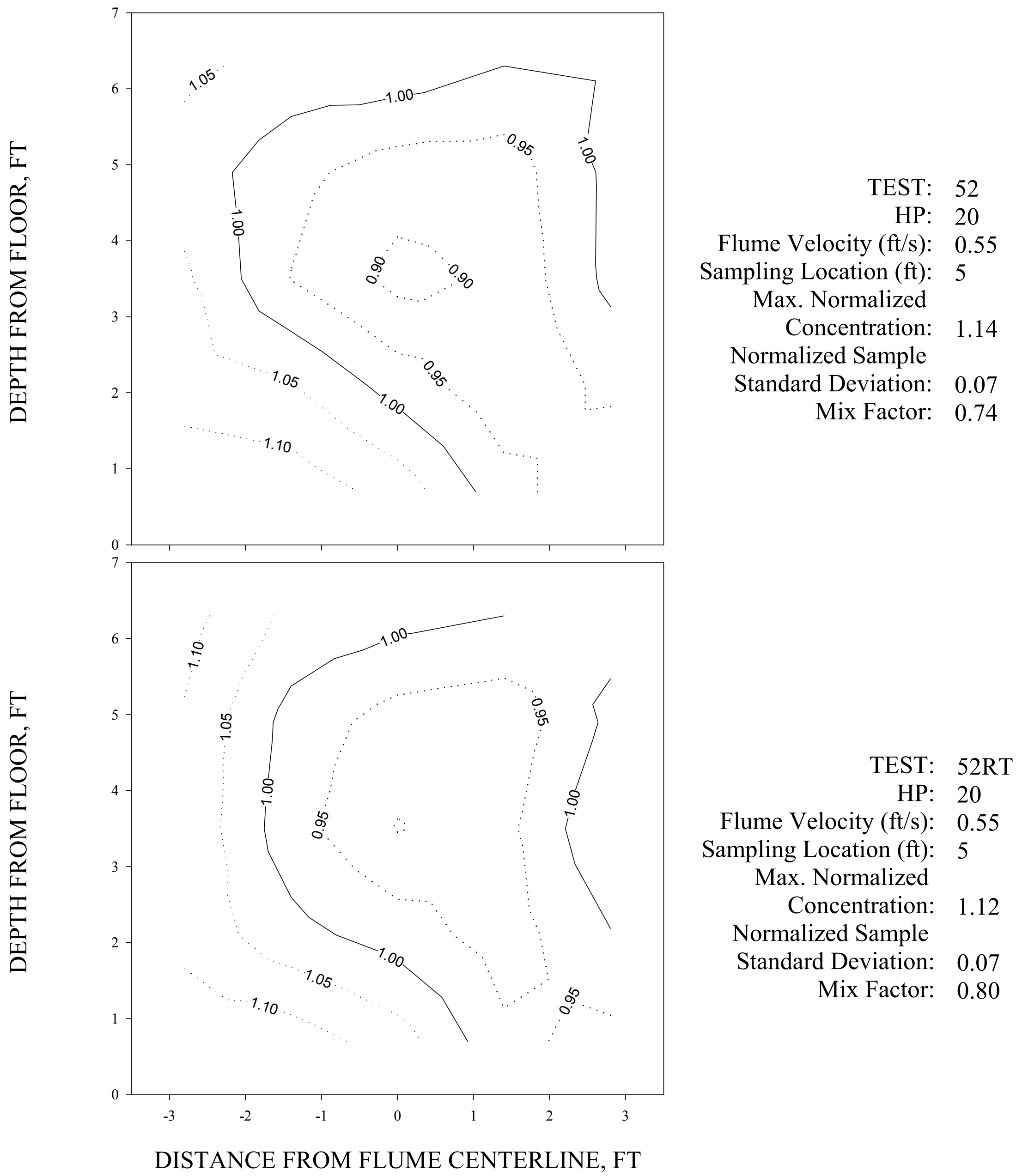


Figure 6.3: Comparison of Original and Repeat Testing—Non-Dimensional Concentration Distribution For The 20 HP Mixer at 0.5 ft/sec Flume Velocity

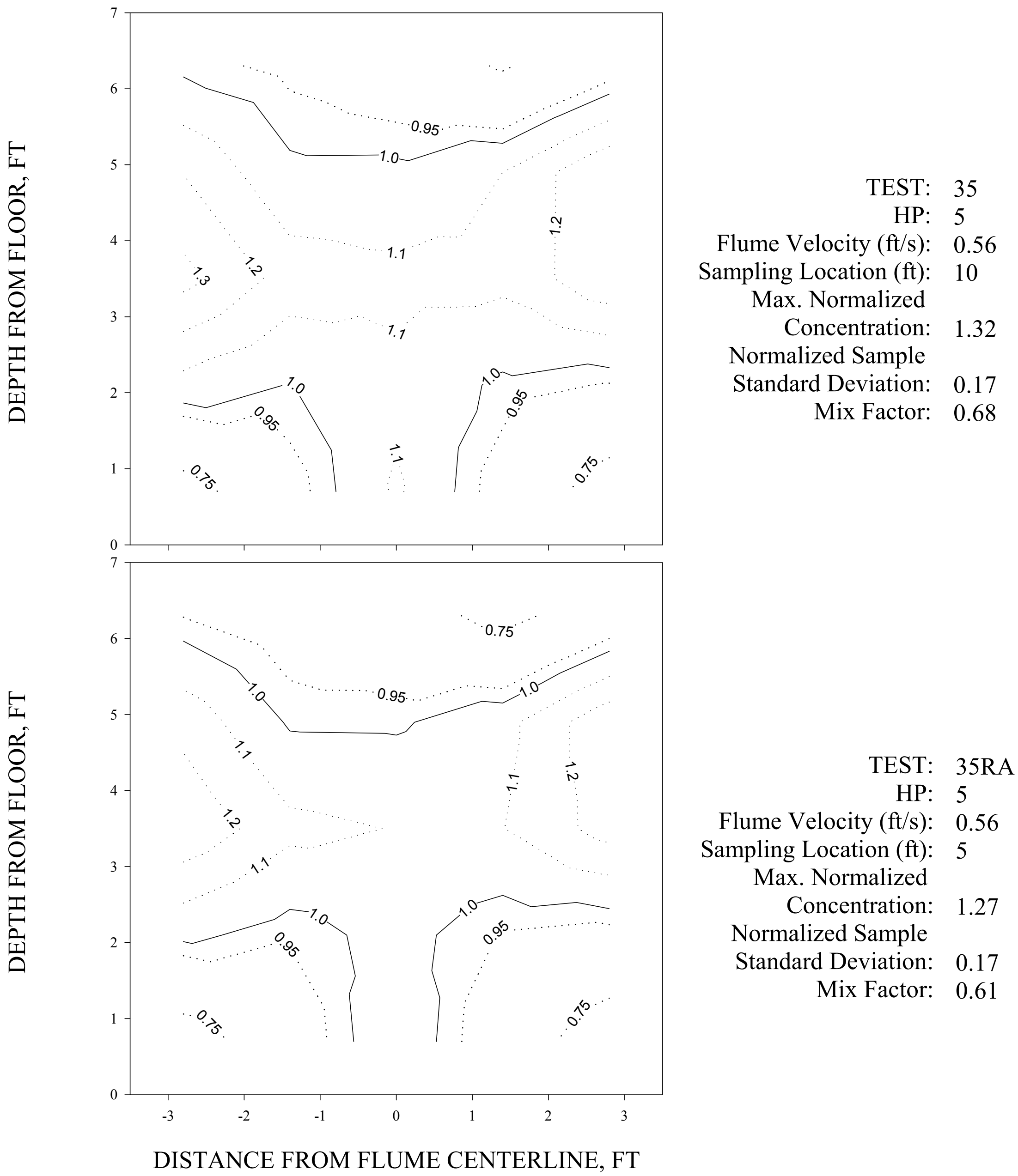


Figure 6.4: Comparison of Original and Repeat Testing—Non-Dimensional Concentration Distribution For The 5 HP Mixer at 1.25 ft/sec Flume Velocity

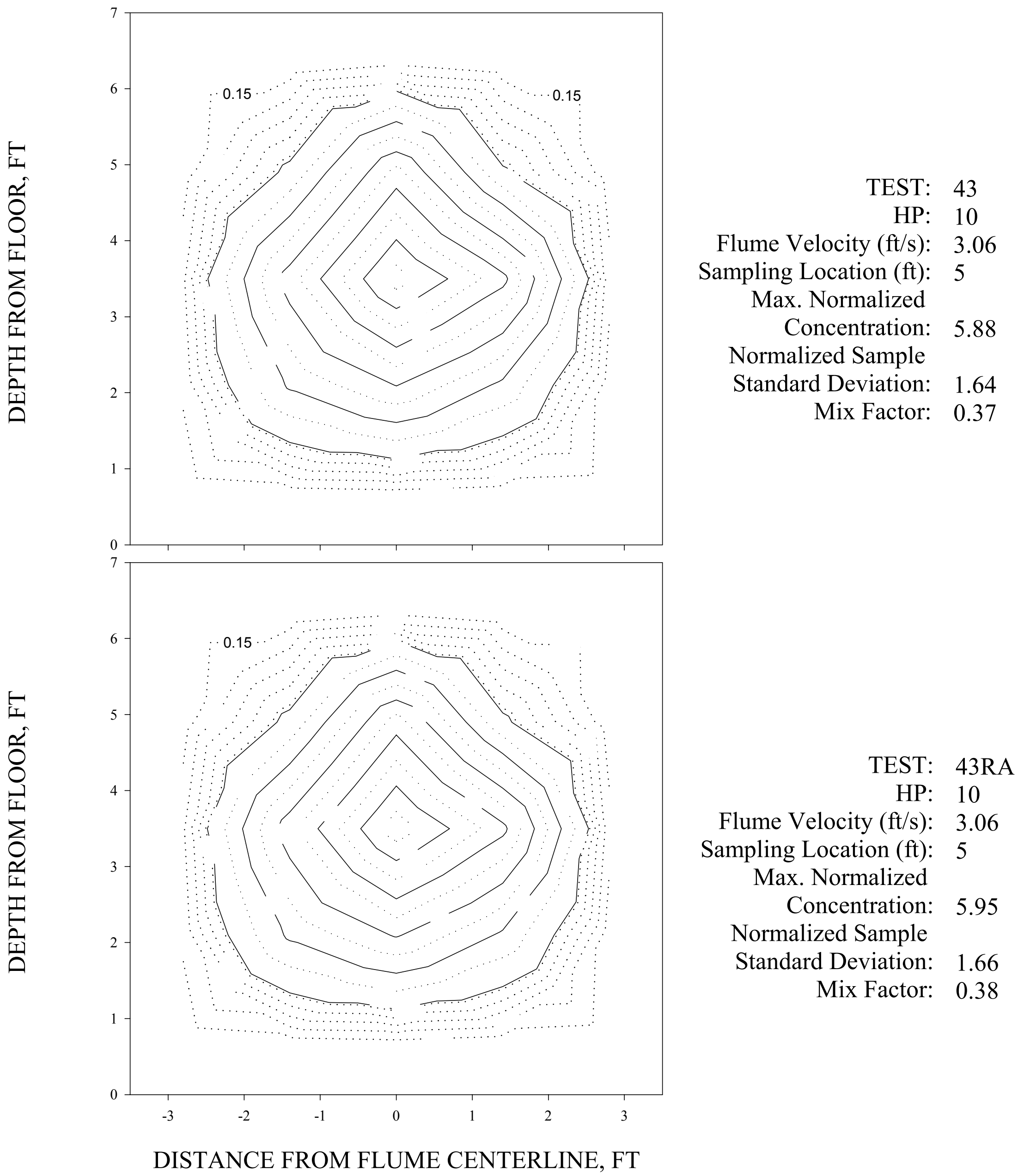


Figure 6.5: Comparison of Original and Repeat Testing—Non-Dimensional Concentration Distribution For The 10 HP Mixer at 3.0 ft/sec Flume Velocity

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